WASTE-TO-ENERGY DECISION SUPPORT METHOD FOR FORWARD DEPLOYED FORCES

THESIS

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Abstract

Solid waste is generated in mass quantities at forward deployed locations due to their temporary nature. Current handling practices are inefficient and wasteful, and do not reuse the energy inherently available in the waste. This research identifies potential energy, convoy, and casualty reductions that can be realized through the use of waste-to-energy (WTE) at contingency locations. It identifies typical variance expected in the solid waste stream and illustrates decision factors for determining the type of WTE technology that is best suited for a particular situation. A statistical analysis was conducted on the waste streams of five contingency bases to determine energy content of a typical sample at any location for WTE planning purposes. Energy and risk reduction was calculated and a decision tree was developed to allow personnel to choose a technology type that would best suit their waste disposal needs. Results indicate that variability in the waste stream significantly affects results of each analysis and that the typical sample energy content from the entire waste stream is much lower than either of the other waste streams. This indicates that energy content is diluted when all waste is combined and higher energy content is present in waste from specific activities.

This work is dedicated to my wife who never let me accept anything less than my absolute best.

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Daniel C. Amack

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I. Introduction

Background

There are currently 150 Waste to Energy (WTE) plants in the United States that combust approximately 50 million tons of Municipal Solid Wastes (MSW) (Gershman and Hammond 2012). Current waste generation amounts are following an ever increasing trend; between the year 2002 and 2004, MSW increased at a rate of 2.5% (Loeser and Redfern 2008, 1-4). Approximately 64% of MSW generated is landfilled followed by 28.5 % being recycled and 7.4% handled in some form of WTE process (Loeser and Redfern 2008, 1-4). With the cost of energy increasing and the supply of readily available petroleum products diminishing (Hirsch et al., 2006, 2-2-8), countries around the world are beginning to invest more heavily in WTE technology (Hirsch et al., 2006, 2-2-8). According to the United States Environmental Protection Agency (EPA), each person in the United States generates 4.43 pounds per day of MSW with a combined total of 249.9 million tons. From the year 2000 to the year 2010, the number has stayed relatively constant thus generating approximately 2.75 billion tons of MSW over a ten year span (US EPA 2013). This generation of waste has significant potential to generate energy for the United States.

The U.S. Air Force Energy Strategic Plan added a new core priority in March 2013 focusing on energy resiliency. Energy resiliency addresses issues pertaining to the vulnerabilities associated with the current energy posture of the United States Air Force (USAF). The intent is to identify vulnerabilities to energy and water supplies and to mitigate impacts from disruptions in energy supplies and critical assets, installations, and priority missions (USAF, 2013). Guidance set by this plan assists the USAF in developing the means to increase energy security on contingency and main base installations. The other priorities of the plan, Reduce Demand, Assure Supply, and Foster an Energy Aware Culture (USAF 2013), also provide a long range goal for any energy initiative undertaken by the USAF.

The USAF can benefit from WTE in all four of the strategic plan priorities: Improve Resiliency, Reduce Demand, Assure Supply, and Foster an Energy Aware Culture. Many contingency locations rely on a constant source of fuel to produce mission essential power requirements. The fuel is generally delivered by convoy to each installation and each convoy encounters various risks on route to the installation. Risks include improvised explosive devices (IEDs), hazardous road conditions, and many other unpredictable events.

WTE uses the solid waste generated by personnel at each installation as a source of fuel to create mission essential power. By incorporating WTE into normal contingency operations, disruptions in the supply chain can be minimized because the supply requirement is reduced. Currently, the Air Force relies on the delivery of petroleum based fuels for energy produced in deployed locations, the delivery of which requires primarily the use of vehicle convoy operations through hazardous areas (Eady et al. 2009). In combat zones, approximately 750 soldiers are wounded or killed guarding resupply convoys each year (Leno 2013). Waste to energy projects have the capability to offset the security risks associated with convoy operations and reduce the reliance on the fuel. If each forward operating base (FOB) were to incorporate some means of WTE technology, it would add a measure of self-sufficiency to their daily operation, no longer being as reliant on a supply of fuel being sent to their location. WTE could also reduce the risk associated with being without power for any amount of time as power would be generated on-site and access would not be an issue.

In the U.S., MSW is primarily composed of paper, food, plastics and yard trimmings with trace amounts of other materials (U.S. Army Logistics Innovation Agency 2013). In deployed locations, the mix is approximately similar with the exception of an increased amount of food, plastic and wood waste and a complete lack of yard trimmings (U.S. Army Logistics Innovation Agency 2013). These materials contain energy that can be recovered; one ton of MSW can produce approximately 550 kilowatt hours (kWh) of energy while 1 gallon of diesel produces only 14.2 kWh in a 33% efficient generator (Mendoza 2013). Waste to energy can provide environmental and energy benefits to military members and the local populace in deployed locations. Because there is significant production of energy through this technology, there are also high potential monetary savings if used to create energy efficient military installations at deployed locations. The technology offers many benefits to the USAF in the form of reduced energy costs, HAZMAT and sensitive material disposal cost reduction, diversifying the energy portfolio and assisting the government in meeting renewable and alternative energy mandates. It has the potential to reduce the number of resupply sorties and the associated losses from them; WTE can provide a cleaner work environment by reducing the use of open burn pits that can be used by adversaries to identify the location of the base, and allow for faster base deconstruction and demobilization.

Research Objective

The objective of this research was first to *determine if solid waste characteristics at five contingency bases are location or mission dependent*. If the waste generated by United States forces abroad is similar from one location to the next, regardless of the mission of the base, it could then be considered as a planning factor for those developing the technology. This fact could potentially swing the focus away from systems designed for a specific purpose and allow developers to focus more on an off-the-shelf system that will suit the needs of all installations. The secondary objective of this research was *to determine the risks that can be avoided by using WTE in a deployed setting, specifically focusing on the reduction of casualties experienced from convoy fuel re-supply missions*. Waste generated at a base can be directly converted into usable energy that will produce real savings, both on the amount of fuel necessary for contingency operations and the cost needed to sustain the current operations tempo. A final objective was *to develop a decision model for WTE technology selection in a deployed location* in an effort to help personnel determine the "best" option for their current situation. The "best" option would be the type of technology that would suit that installation's specific WTE goals. WTE systems are typically designed specifically for the location they are used in (Stehlik 2009), and this method of WTE implementation does not work well for the USAF, due to the number of unknowns associated with a FOB style of life. When WTE technology is further developed and "off the shelf" units become more common, this decision model can be used to point base personnel toward or away from certain types of systems based on the information they can gather.

The concept of WTE as a renewable resource is relatively new to the military and, as such, it is less mature than other renewable resources and more difficult to incorporate. In order to determine if a FOB is ready to implement WTE, it would be necessary to determine if a sufficient amount of waste, with a high energy potential, is available at a location. To determine the available energy potential in waste generated at a FOB, a waste characterization analysis would be necessary in order to identify the types and quantities of waste present at an installation. Provided that a sufficient amount of waste is present at a FOB, base personnel would need to analyze various other aspects of their waste management system in order to select the appropriate technology to suit their needs. The specific research questions considered by this research are presented below:

1. How does waste stream variation compare at the five locations?
2. How can we consistently quantify risk based on WTE opportunities?
3. What decision elements should be included in a WTE decision model?

Research Approach

The research was conducted in three phases. First, a literature review was conducted to identify recent developments in the WTE field. Secondly, analysis of waste characterization data presented by the U. S. Army Logistics Innovation Agency (2013) identified the waste streams at military contingency bases. A statistical analysis consisting of a study of the median and Interquartile Ranges (IQR) of the waste categories, along with using the Wilcoxon's rank sum and Brown-Forsythe tests to examine similarity and variance, was conducted to determine the variability between different aspects of the waste management systems. The statistical analysis provided the basis to infer waste characteristics about Afghanistan and Kuwait as a whole. From the data, the author was able to make predictions of potential energy savings on a per person basis for a typical Air Force base. The size and type of a WTE unit is highly sensitive to waste volume and energy content. This step is crucial to the success of a WTE project because without the proper amount and type of waste, a modular unit would not be successful after the costly amount that is spent to transport it to a contingency base. Lastly, a basic decision model was developed to assist personnel with planning factors associated with WTE system selection. This model, a decision tree, considers some of the common situations that would occur at a contingency base and identifies a technology that would be beneficial.

Assumptions and Limitations

A number of assumptions had to be made in order to conduct certain aspects of the analysis. A list of all assumptions made is presented below.

Assumptions:

1. The power generation components at a "typical" installation are consistent with the Harvest Falcon generator set described in Chapter 2.
2. The kilowatt hour (kWh) per person calculations are assumed to remain constant, regardless of the actual population at a base. This was necessary to facilitate general energy calculations.
3. This research does not take the initial purchase and shipment costs of any particular system into consideration. Calculations are based on the energy potential present in the waste alone.
4. At a forward operation base, decision makers prioritize risk reduction over cost avoidance.

Limitations:

1. WTE technology is dynamic, new requirements and systems are constantly being created.

2. Due to a lack of information on physicochemical waste to energy transformation, that particular form of energy was not discussed in this research. Plasma type energy conversion techniques are also not considered, due to the high requirement of a stable electrical source to generate the plasma.

II. Literature Review

Chapter Overview

This chapter provides the essential knowledge of Waste-to-Energy (WTE) technology and its feasible applications within the USAF. It was utilized to determine the risk associated with adopting the technology in a contingency location, as well as establishing the need for energy technology. The chapter discusses the different types of WTE and their uses for the United States Air Force. It starts by identifying congressional and military regulations associated with open pit burning, along with energy reduction requirements. Next, the Air Force's strategic plans are discussed to outline how the Air Force plans to make changes to the current energy usage. This section also provides the basis for why WTE should be pursued in the Air Force. It then outlines the requirements for contingency bases in terms of fuel and risk, which provides the basis for the risk calculations presented further in the report. Specific WTE technologies are then discussed to identify the basic requirements for each of the technologies considered by the report. Waste stream statistics and general statistical analysis methods are discussed to identify the type of analysis conducted by the researcher. The Harvest Falcon beddown set is discussed as a basis for a per person fuel usage rate used to calculate the reduction of risk that can be associated to WTE technology. Finally, decision tree diagrams are discussed to illustrate the factors that must be considered when deciding on a WTE technology.

Congressional and Military Regulations

The National Defense Authorization Act (NDAA) of 2009 requires the Department of Defense (DoD) to enforce regulations prohibiting the disposal of covered waste in open-air burn pits during contingency operations, except where the Secretary of Defense (SECDEF) has determined no alternative disposal method is feasible (Congress 2009, 317). The act requires the SECDEF to submit reports to Congress identifying locations where open burning is taking place and why alternative means of waste disposal are not feasible. Reports are also submitted outlining health and environmental compliance standards established for military personnel and contractors in areas where open burning is permitted; the health and environmental impacts are also described in these reports. A subsequent revision to the NDAA in 2011 requires epidemiological descriptions of short-and long-term health risks posed to personnel in the areas where open-air burning is permitted. The NDAA illustrates the significance Congress places on the disposal of solid wastes in contingency locations. This has led to several military instructions and directives intended to reduce the hazards related to open-air burning which is a primary concern for the SECDEFF. With this act in place it has prompted many organizations to take a serious look at the way solid waste is managed; both third party contractors and military organizations have developed possible solutions to the waste management problem. According to one of these reports presented to Congress in 2010, the preferred method of solid waste disposal during military operations worldwide is through commercial contracting directly with local national or host-nation service providers or through standing contracting instruments available to military commanders

(Thomas et al. 2010). If this is not possible, the following four options can be explored (Thomas et al. 2010):

a. Develop or contract for US operated or controlled landfills
b. Purchase, lease, or contract for incinerators
c. Collect and transport waste to a location where either landfills or incinerators are available
d. If a, b, and c are not available, use open air burn pits IAW [DODI 4715.19]

These options are in priority order and every effort is made to limit the amount of open-air burning conducted in the United States Central Command (CENTCOM) Area of Responsibility (AOR). At the time of this report's publication, open-air burn pits were not used outside of the CENTCOM AOR. The preferred method of disposing of solid wastes in the AOR is by burning; burning trash not only reduces the overall volume of the trash, but it also helps to limit the spread of disease by vectors attracted to the waste material (CENTCOM 2012).

Congress and the DoD have placed great emphasis on the importance of waste management in a contingency location and have both identified the importance of thermal destruction of trash, while simultaneously agreeing upon the negative aspects of open-air burning. But, is the disposal of Municipal Solid Waste (MSW) the primary concern and any energy gained from WTE technologies would simply be a bonus, or should the energy production be maximized? According to Mr. Diltz, a member of the Air Force Research Laboratory (AFRL) at Tyndall AFB in Florida, a WTE system that requires 2 Watts (W) to run and produces 1 W is considered a success in a deployed setting. This could lead to the conclusion that volume and risk reduction are more important than actual energy production. This conclusion is, however, based off of today's technology.

Over time, the use of WTE could become so common that systems will eventually be robust enough to be used anywhere in the world with high energy outputs.

Various other executive orders and federal legislation can also be met, in part, by the use of WTE. Executive Order 13423 (2007) requires "federal agencies to reduce energy intensity by three percent annually or 30 percent by end of fiscal year 2015…" It also looks for the reduction of total petroleum consumption in vehicle fleets. Both objectives can be met with the use of WTE through the production of syngas which, after refinement, can replace diesel fuel in vehicles. Executive Order 13514 (U.S. President, 2009) calls for a reduction in greenhouse gases, a reduction of energy intensity in buildings, an increased use of renewable energy and reduction of fossil fuels in vehicles. Other federal legislation exist that call for various forms of energy or greenhouse gas reductions along with fuel reduction and overall energy reduction. Implementation of WTE in the AOR would reduce greenhouse emissions due to open burning (RTI International 2012), reduce the amount of fuel delivered to the AOR for electricity production, and reduce costs associated with waste disposal contracts (Wagner 2007).

U.S. Air Force Energy Strategic Plan

Every mission the DoD is involved in requires energy: "From aviation operations to installations and ground vehicles within the homeland and abroad, energy is essential for Air Force operations and a key to our national and economic security" (USAF 2013). The USAF Energy Strategic Plan outlines four priorities to ensure the security of energy in the future: Improve Resiliency, Reduce Demand, Assure Supply, and Foster an Energy Aware Culture. These priorities will help to incorporate energy considerations in all actions taken by the Air Force. The objectives of improving energy resiliency involve identifying vulnerabilities to energy supplies and safeguarding them from physical and cyber attacks or natural disaster (USAF 2013). Resiliency also attempts to mitigate disruptions to the current energy network. Resiliency can be met with WTE by providing an alternate means of energy generation. Most forward operating bases (FOBs) generate electricity, a critical mission component, by use of generators. If a fuel supply issue were to occur, this critical asset could be threatened. WTE provides a means to reduce or even eliminate the risk of a fuel supply issue and can help ensure a constant supply of energy is available to a FOB.

Forward Operation Base Logistics

The fundamental consideration in forward deployment is logistics (SERDP 2010). Throughout history, the availability of logistical support has played a key role in success of military operations. Logistics operations in the Department of Defense (DoD) require half of the available personnel and consumes a third of its budget (SERDP 2010). Supply lines in Afghanistan are especially difficult as it can take supplies up to 45 days to travel from the source to the end user (SERDP 2010). Every item that is shipped to the AOR must satisfy a specific need or else it is just a waste of fuel and unnecessary risk to soldiers who operate the supply lines. In Afghanistan, a FOB of 600 personnel would rely on a convoy of 22 trucks each day to provide for fuel or water and to truck away wastewater and solid waste (SERDP 2010). With these logistical requirements, reductions in both fuel consumption and volume of waste are clearly important. If energy can be produced at contingency locations, even in small amounts, it can alleviate pressure from dangerous fuel supply routes (Department of Defense 2011). Convoy operations in Afghanistan are very dangerous and have resulted in the deaths of many soldiers over the years that the United States has conducted operations in Afghanistan. In June 2008, 44 trucks and 220,000 gallons of fuel were lost due to insurgency attacks and other factors (Deloitte 2009). Renewable energy technologies can decrease the amount of fuel resupply convoys necessary to continue operations. A significant decrease in the number of resupply missions needed would decrease the amount of lives and assets lost in convoy operations.

Fully Burdened Cost of Fuel

The overall supply chain for fuel in the AOR starts with the Joint Petroleum Office in theater setting the fuel consumption and planning requirements, based on current and future operations. Defense Logistics Agency (DLA) manages the material and the Defense Energy Support Center (DESC) arranges the contracts and procures the fuel from a nearby source (DoD 2013). DESC coordinates with U.S. Transportation Command or other agencies to arrange transport of the fuel outside of the operating areas. Once fuel is delivered to a hub in theater, responsibility is handed off to the service elements to distribute (SERDP 2010). Complications such as safety, diversification of sources, difficult terrain, poor quality roads and harsh weather create long wait times for fuel. These complications make it very difficult to determine a true fully burdened cost of fuel.

Many variables must be taken into consideration to accurately determine the amount of fuel needed to supply an installation with power. One burden on any contingency operating base is the Heating, Ventilation and Air Conditioning (HVAC) loads (McCaskey 2010; Murley 2013). HVAC energy demands account for approximately 59 to 67 percent of the overall Base Operation Support (BOS) power consumption (McCaskey 2010). The primary source of power in contingency locations comes from the use of generators where the MEP-012A generator is the standard for prime power generation (McCaskey 2010). The generator produces 750 kilowatts of power with a fuel consumption of 55 gallons per hour (Department of the Air Force 2008). This does not include the fuel expended for transportation to the location. Deloitte performed a study in 2009 in which they analyzed the fuel consumption of a soldier in current military operations, using a base price of $2.14 per gallon of fuel. In the study, they illustrate that this cost drastically increases when factoring in every resource that is used to transport the fuel to the end user. Without taking any protection aspects into account, the cost of fuel quickly rises to around $15 per gallon, a 700% increase from the base cost (Deloitte 2009). When also including the number of vehicles (land and air) it takes to protect a fuel convoy, the cost increases to around $25, a 1,168% increase, per gallon. Long roads and the risk of improvised explosive devices (IED) can further increase the cost of fuel to approximately $45, a 2,100% increase (Deloitte 2009). The current price for diesel fuel, which is used for power generation, is $3.73 per gallon (DLA 2013). Using the current price and the same percentage increases, we can infer that the approximate cost could be between $26 and $78 per gallon for the year 2013.

As of 2007, fuel consumption for soldiers in Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) was 22 gallons per soldier per day, a 175% increase since Vietnam (SERDP 2010). Using the numbers above, that equates to between $200,750 and $666,490 a year per soldier.

WTE Technology

Waste-to-Energy (WTE) comes in four main forms: direct combustion, physicochemical, thermal and biological (Bosmans and Helsen 2010; Morgan 2013). Due to a lack of information, physicochemical waste to energy transformation was not addressed in this research. Further, plasma type energy conversion techniques are also not considered, due to the high requirement of a stable electrical source to generate the plasma.

Thermal WTE technology includes three subtypes called incineration, gasification, and pyrolysis. There are two main forms of biological WTE technology known as anaerobic digestion and fermentation (Bosmans and Helsen 2010). Figure 1 below illustrates the possible methods of energy conversion and the following sections will outline the different technologies.

Direct Combustion

Direct combustion WTE, also known as incineration, is the most mature known technology of its type with its first use recorded in the late 1800s. In the early days, it was primarily used for waste disposal and was later used for disposal and energy recovery (Morgan 2013). This type of technology is widely used in the European Union today; however, it is not widely used in the United States, primarily due to common misconceptions about incineration technology producing toxic emissions (Morgan 2013).

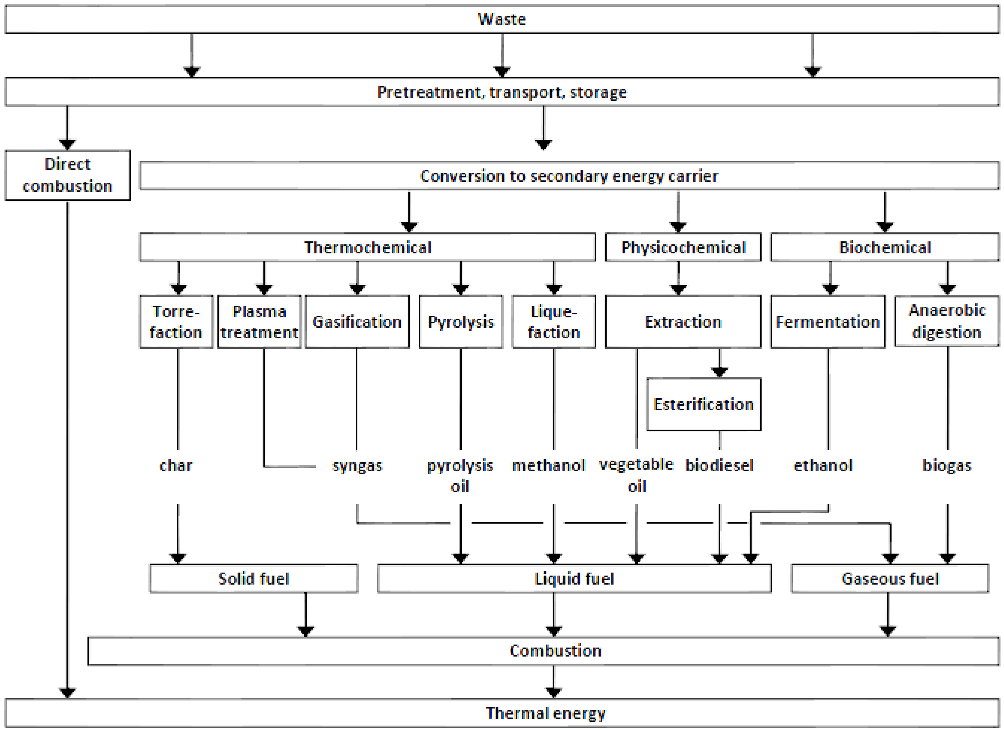


Figure 1: Waste-to-Energy technologies (Bosmans and Helsen 2010)

Incineration technology can be extremely beneficial due to the fact that it can utilize waste that would otherwise find its way to landfills and convert it to electrical power. Hazardous materials can also be destroyed using incineration which helps to meet environmental standards (Morgan 2013). Incineration is a well proven technology and some companies offer portable units as well (Zanni-Tech 2014). Incineration technology provides a means to reduce the volume of waste while simultaneously producing energy and can be used to treat a wide range of wastes (Bosmans and Helsen 2010). Though the technology is proven, it is not entirely without drawbacks as the process does produce fly ash and some toxic emissions. However, both problems can be significantly reduced with the use of thorough waste presorting methods. A significant drawback impeding the implementation of the technology is an unfavorable public perception associated with the emissions produced by the technology.

Gasification

Gasification is a thermal process in which thermal energy is used to convert carbon based materials into Syngas ($CO + CO_2 + H_2$), a synthetic gas, in an oxygen starved atmosphere (Jianfen Li et al., 2010). This process has also been available since the 1800s, as it was used to make "town gas" for street lights (Morgan 2013). This process can be used to convert many carbon sources (wood, coal, charcoal, plastics, and biomass) into useable fuel (Jianfen Li et al. 2010, 530-534). The process has only recently been used for waste disposal and WTE activities. Syngas produced from the gasification process has been shown to directly replace gasoline in internal combustion engines and can be used as a source for hydrogen fuel cells (Jianfen Li et al. 2010, 530-534). The Syngas can also be upgraded via a Fischer-Tropsch process to gasoline, diesel, or jet fuel (Morgan 2013). Emissions issues associated with gasification tend to be minor when compared to incineration, which leads to a much easier environmental permitting process. The quality of the Syngas is dependent upon the waste stream available to the system, significant downtime during the process can be costly, and public perception issues associating the technology to that of incineration must be mitigated (Morgan 2013). High variation in the waste stream can increase the likelihood of these drawbacks and reduce efficiencies, thereby making a gasification system difficult to justify economically. If the content of waste varies significantly, the available energy content may not be high enough to produce a good quality product.

Pyrolysis

Pyrolysis, also known as cracking, is a thermal process in which the decomposition of carbonaceous materials takes place in the absence of oxidizing gases (Li Xin-yue et al. 2011, 336-340). This process yields gaseous products, liquid products (various oils) and solids (char and non-combustibles). The efficiency of this process varies greatly depending on the amount of plastic present in the waste stream and is most efficient when the waste stream has a high plastic content (RTI International 2012). It is efficient at breaking down plastics, but loses efficiency when the amount of plastic is low and thus it is not suitable for all waste streams (Li Xin-yue et al. 2011, 336-340). According to an RTI International Report (2012), 100 tons of plastics could generate enough energy for 550-1100 homes. A typical pyrolysis process is presented in Figure 2 below.

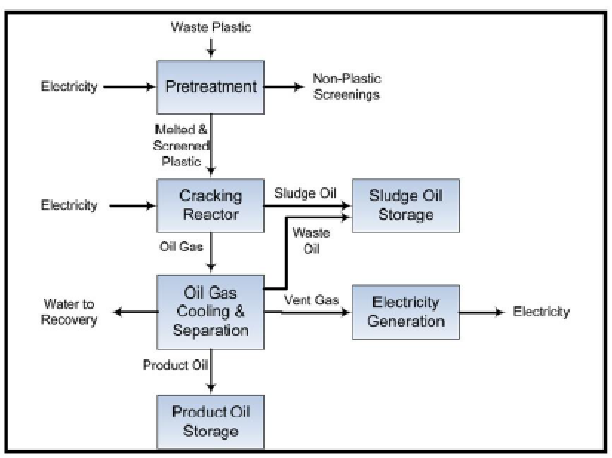


Figure 2: Envion Pyrolysis Process Flow Diagram (Source: www.envion.com)

Anaerobic Digestion/Fermentation

The processes of anaerobic digestion and fermentation involve the conversion of biomass, cellulosic materials, and food waste into hydrogen, methane, ammonia or ethanol (Zhang and Ma 2006, 2262-2267; Wagner 2007). Both processes utilize bacteria to convert biomass to biogas, a mixture of methane and carbon dioxide (Zhang and Ma 2006, 2262-2267; Strange 2010). The anaerobic digestion process takes place when the waste has restricted aeration and the resultant methane mixture can be combusted for electricity or heat production (Wagner 2007). This is also a naturally-occurring process present at the bottom of lakes and wetlands and contributes to the addition of greenhouse gases. The fermentation process converts organic wastes to ethanol through bacterial fermentation (Wagner 2007). In both processes, bacteria that create the gases in the process are highly susceptible to variations in the environment, such as temperature and pH levels (Strange 2010). Optimal temperature and pH levels differ depending on the waste that is being digested (Strange 2010); large variation of wastes could change the required conditions for this process to be maintained. This process could also require sophisticated monitoring that may not be available in a contingency environment.

Waste Stream

There are many possible ways to create energy from the waste streams that are produced by humans; however, it is important that each technology used is chosen only after an analysis of the waste stream that will serve as the input to the WTE system. Each conversion technology is sensitive to the type of waste fed into the system. Without the proper waste, the efficiency of the process will be too low to produce the required levels of energy production. At this time, no universal system exists with the capability to convert all types of wastes with a high level of efficiency and, therefore, it is critical to analyze the waste stream before a specific technology is selected.

The analysis of waste in a contingency location is important because the WTE technologies significantly depend on the waste stream. The waste distribution would determine which type of energy conversion technology could be used in each location. An analysis of five contingency locations was conducted by the United States Army Logistics Innovation Agency (USALIA) and published in January of 2013. The study analyzed the waste streams of each location, identifying tons generated per day among other important characteristics (Leno 2013; U.S. Army Logistics Innovation Agency 2013). The report is known as the Contingency Base Waste Stream Analysis (CBWSA). According to the report, the characterization of waste at each contingency location was similar to waste characterizations in the continental United States, with the exception of a lack of yard clippings at the contingency bases. The Table 1 illustrates the results from the report.

Waste stream analysis is critical to determining which form of WTE system to install. Based on the consistency and energy output of the waste stream, certain technologies are more appropriate to use, thus increasing output and decreasing costs. By utilizing data collected from the study, a range of possible outputs could be developed based off of the latent energy contained in the typical samples. During the CBWSA study, solid waste was collected from random sampling points around each installation. The sampling technique determined the amount of each waste type disposed of at each location. However, waste characterization can have a high level of variance present in the waste depending on the approach used to characterize waste. The current standard for waste characterization is set by ASTM international; this standard was followed by the USALIA when the report was conducted.

Table 1: Detailed Solid Waste Composition by Base (MSW, Percent by weight) (U.S. Army Logistics Innovation Agency 2013)

	Waste Component	CB #1	CB #2	CB #3	CB #4	CB #5	Afghanistan Avg (Weighted)[b]
Corrugated Cardboard		9.5%	15.10%	9.3%	13.1%	16.2%	13.7%
Food Waste		15.5%	20.70%	24.5%	15.5%	24.6%	19.1%
Liquid		NR[b]	5.80%	7.4%	7.3%	6.4%	6.6%
Miscellaneous Waste		5.1%	1.10%	3.6%	1.5%	2.0%	1.6%
Mixed Paper		28.8%	13.30%	10.5%	14.4%	5.3%	13.2%
Non-Combustible	Ferrous Metal	1.2%	3.30%	5.7%	2.4%	3.5%	3.2%
	Non-Ferrous Metal	2.3%	1.80%	2.0%	1.4%	1.1%	1.6%
	Glass	1.0%	0.20%	0.2%	0.2%	0.7%	0.2%
Other Combustible		5.5%	0.50%	2.2%	2.2%	0.8%	0.5%
Plastics	#1- PET	10.6%	7.00%	5.5%	6.1%	3.2%	6.4%
	#2 - HDPE	5.0%	5.40%	4.2%	1.6%	1.6%	3.7%
	#3 - PVC	4.4%	0.70%	0.8%	0.5%	1.2%	0.7%
	#4 - LDPE/LLDPE	1.3%	2.80%	1.9%	3.1%	1.0%	2.8%
	#5 - PP	0.1%	0.20%	0.3%	0.2%	0.1%	0.2%
	#6 - PS	7.3%	2.20%	1.0%	1.2%	1.0%	1.6%
	#7 - other	0.1%	0.70%	0.4%	0.6%	0.5%	0.6%
Total Plastic (All Types)		28.8%	19.00%	14.1%	13.3%	8.6%	16.0%
Textile		1.3%	5.40%	4.1%	5.6%	3.0%	5.3%
Wood		1.0%	13.70%	16.5%	25.3%	27.0%	18.9%
Total		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

[a]Due to rounding, some percentages different from some other tables and figures and some totals do not add up to 100%. Percentages generally rounded to nearest tenth of a percent.
[b]Averages for Afghanistan bases weighted in proportion to the base total weight of waste processed annually. Refer to appendix C for more information (page C.9).

When separating waste, there will inevitably be a miscellaneous category that can contain various wastes that cannot otherwise be categorized. These miscellaneous wastes can make it problematic for selecting WTE technology, especially if the percentage of waste in the miscellaneous category is relatively high. In the report from the USALIA, the miscellaneous category has a maximum of 5.3% by weight for each of the bases and it can be assumed that the miscellaneous portion of the waste will not have a significant impact on the overall energy content of the waste.

Statistical Analysis

A statistical analysis was required to determine if the waste data collected by USALIA could be assumed to be consistent throughout the countries of Afghanistan and Kuwait. If consistent, then certain assumptions can be made about waste generated at other operating locations in each of the countries. The data generated by the report consisted of various samples from five bases, four in Afghanistan and one in Kuwait. Each sample consisted of waste collected from a single point where the waste was categorized by weight in the following categories: corrugated cardboard, food waste, liquid, miscellaneous waste, mixed paper, non-combustible, other combustible, plastic, textile, and wood (U.S. Army Logistics Innovation Agency 2013). Data were also provided to indicate what type of activity generated each sample and the activities listed in the report were Dining Facility (DFAC), Administrative (Admin), Motor Pool, Life Support Area (LSA), Supply Support Activity (SSA), and General. Many samples contained only waste from some waste categories, leaving the remaining categories with values at or near zero. This resulted in a skewed data set for nearly each sample taken; an example of a particular data histogram can be viewed in Figure 3.

The skewed nature of the data presented makes it difficult to make assumptions about the nature of the data based on the mean values alone. The data itself is not normally distributed and even if an unlimited amount of samples were taken, the data would still have skewed properties similar to that presented above, as there may be instances where certain waste categories are not present in a sample. At the onset of an investigation, the true distribution of the data is unknown; therefore the statistical methods used are nonparametric in nature (Moore and McCabe 2003).

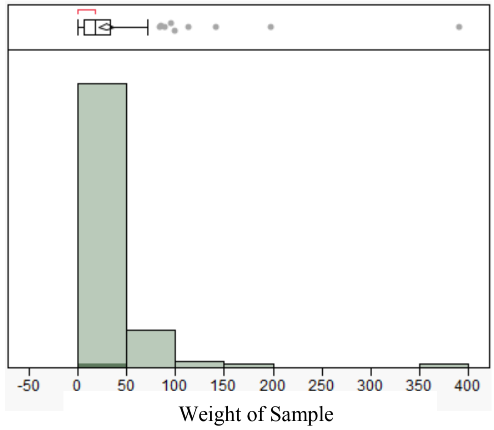


Figure 3: Data Histogram for Corrugated Cardboard data points (lbs)

In the case of nonparametric tests, no assumptions are made about the distribution of the data and the mean and the medians are assumed to be not equal. Since the data is skewed, the median is a better measure of the center of the data than the mean (Moore and McCabe 2003). Therefore, any test that is applied to the data would need to make inferences about the population median and not the mean.

The Wilcoxon rank sum test is a nonparametric test that assigns a rank value to each observation and calculates probabilities based on the rank of the observation rather than the value of the observation itself (Moore and McCabe 2003). This test was appropriate for the given data, due to the skewed nature. By assigning a rank value to the observations, the test disregards the distribution of the data and focuses on where observations rank when compared to each other. There are several tests in statistics that utilize a similar method; however the Wilcoxon rank sum test is specifically used when there are two independent samples being analyzed (Moore and McCabe 2003). The two independent variables in this research are the waste category and the location. The hypothesis for the Wilcoxon test is that the median of one distribution is the same as the other distribution, provided that both populations have the same variance (Moore and

McCabe 2003). The Brown-Forsythe test was used to determine if the variance between groups was equal. This test was used because it provides a test statistic of an analysis of variance on the absolute deviations from the median and relies on no assumptions about the distribution of the data.

In order to quantify the variability in the data, a practical value was needed that would maintain the values of the waste categories, in order to determine a minimum thresholds for failure. One of the most basic measures of variation is known as the Interquartile Range (IQR) (Upton and Cook 2007). The IQR provides a range for the bulk of the data and outlines the range of values that comprise the middle 50% of data. Using the IQR provides a physical range of values in which waste values are expected to occur. By using the minimum value and the known weight of diesel fuel, this research identifies where a possible failure point could occur with the given data.

Harvest Falcon Asset

Harvest Falcon is an Air Force beddown set designed to support deployed forces by providing all the essential components needed to support 1,100 people in a contingency environment (Pike 2011). These sets provide everything from billeting and warehouses, to electrical power, sewer, and water systems. The primary interest for this research is the power production equipment delivered by the module. Harvest Falcon comes in a four major component sets: housekeeping, industrial operation, initial flightline, and follow-on flightline (Pike 2011). When all four of these component parts are assembled, they provide everything a force of 1,100 people needs to live and work in a contingency environment. The power production portion of the modules, which provides all electrical requirements needed for daily operations, consists of six MEP-012A, seven MEP-806B, two MEP-805B, and two MEP-806 generators (SERDP 2010). Though not all of these generators are running 100% of the time, they all work in combination to ensure the electrical needs are met. The power generation of these support modules is used as a planning factor for all Air Force bare bases and was used as a baseline for the fuel saving calculations in this report. The Harvest Falcon set has been upgraded to what is now known as Basic Expeditionary Airfield Resources (BEAR). These newer BEAR assets come in different modules and are more appropriately sized for smaller more agile units (Department of the Air Force 2008). However, the power generation components for a BEAR kit that serves the same purpose as the Harvest Falcon sets is identical.

Decision Tree Diagrams

The final goal of this research was to develop a decision model to be used by decision-makers during stable (sustained) base operations. The goal of the model was to incorporate the waste characteristics with known decision factors for WTE. The decision factors consist of a list of factors taken from various sources, including the longevity of the base, amount and variability of the waste stream, location of the base, footprint available to the system, and type of energy desired among other factors (U.S. Army Logistics Innovation Agency 2013; Klopotoski and Simonpietri 2014). The location of the base can play a factor, especially when considering the risk avoidance analysis. If the base is a major transportation hub, or is close to one, then the risk associated with fuel delivery will be different. The footprint available is always a factor when adding any asset to a contingency base. In a deployed environment there is often little opportunity to expand the footprint of a base.

The current goal for WTE systems used for DoD purposes is to have the system modular and containerized. Many of the systems are in some sort of standard shipping container that allows for easy transport and minimal footprint usage. The type of energy desired at the point of use can also play a role in the decision making process.

Some systems generate synthetic gases that can be used directly in standard military generators to produce power, while others produce products that need further refinement before they are able to be used to produce power. If direct power generation is required to sustain a functioning electrical distribution system, then one technology may be preferred over others. Aside from the desired energy output, there is the volume of waste to be considered as well. If too much waste is present, then the primary objective could be simply to reduce the volume of waste and any energy that is recovered would be considered a bonus side effect. If there is not enough waste, then the energy content of the waste alone would not be worth the investment. These factors all combine to make the decision of what system is right for a given scenario very difficult to answer. By analyzing the waste that is generated at installations in Afghanistan and Kuwait, this research will attempt to help with the very complex decision–making process.

A decision tree is a simple way to display the necessary considerations for making a decision. Decision trees can be basic, comprising of only one decision and two possible outcomes. They can also be as complex as incorporating chance and probability with multiple outcomes possible. In either case, they are generally linear in time, with each decision or chance event being experienced in order from left to right (Clemen and Reilly

2001). Decision trees can incorporate risk by including failure possibilities in the diagram. For instance, in a diagram to decide whether or not to invest in a particular financial investment, there is a possibility that the venture could fail and all of the investment could be lost. This decision is illustrated in Figure 4, where the initial decision is to "buy stock" or to "save in bank" the available capital. It further shows the result of each outcome, identifying both a successful and a failed investment. Decision trees can be a simple tool to identify key factors for making decisions, in order to clearly outline possible outcomes of a decision (Clemen and Reilly 2001).

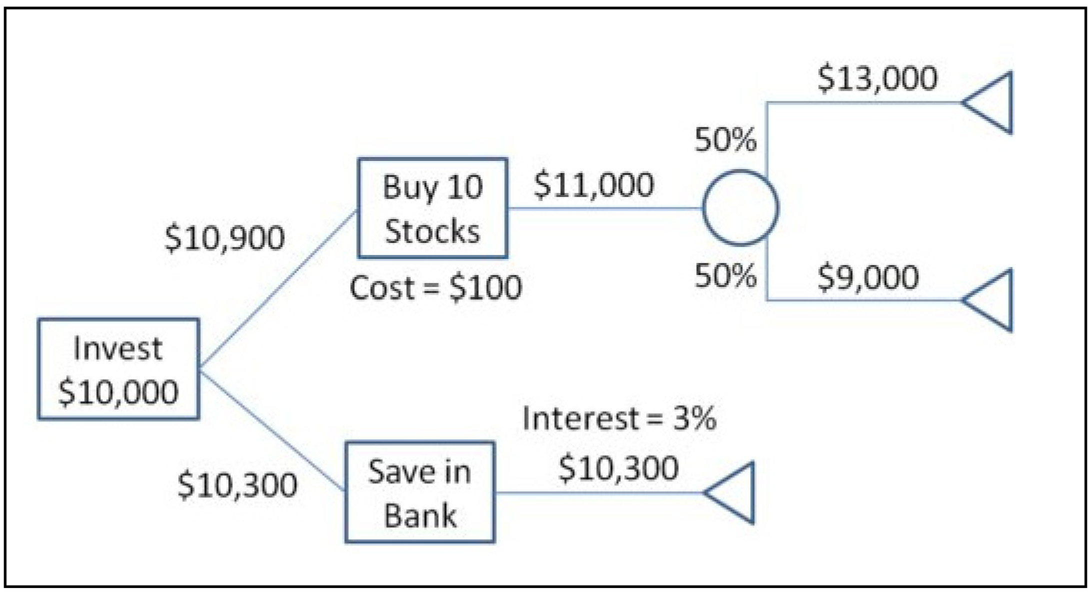


Figure 4: Decision tree diagram (decision-making-solutions.com)

III. Research Approach

Chapter Overview

This chapter describes the research plan and the steps taken to answer the research questions. This methodology combines an analysis of the waste characterization at five contingency locations in U.S. Central Command (CENTCOM), energy content of waste generated at a typical location and its potential for casualty reduction. Finally a decision model is constructed to allow in-place personnel to select a type of technology that would best suit their needs.

Waste characterization is the first and most important step taken before any Waste to Energy (WTE) technology can be chosen. If the waste is not properly characterized, the technology can be rendered useless. Efforts to reduce fuel consumption at contingency locations are one of the prime ways to reduce operations costs and the need for fuel resupply missions, thus saving the lives of those who would be responsible for the delivery of the fuel. A reduction in point-of-use fuel amounts can limit the need for convoy re-supply of fuel, leading to a potential reduction in the number of casualties incurred. The research questions investigated in this research are listed below:

1. How does waste stream variation compare at the five locations?
2. How can we consistently quantify risk based on WTE opportunities?
3. What decision elements should be included in a WTE decision model?

Data Acquisition

As part of planning, it is beneficial to know where to implement the WTE technology. Is the variance of the waste stream low enough to implement the system at the end of the waste stream without pre-sorting, thus utilizing the entire waste stream, or would it be best to place the system within the waste stream only encompassing one or a few activities?

Waste characterization data from locations in U.S. CENTCOM were required to answer the research questions. Data needed to be categorized by waste category and by generating activity, in order to make an accurate analysis of the potential energy available in the waste stream at a contingency base. The data analyzed by this research comes from the United States Army Logistics Innovation Agency (USALIA) and combines the waste characterization from four different bases in Afghanistan and one in Kuwait. The report consists of a data analysis of waste characteristics, generation rates, and other information that can be used as planning factors for potential inclusion of WTE technologies (U.S. Army Logistics Innovation Agency 2013). Key findings from this report include the average amount of waste generated in six different activity areas and the energy that could potentially be recovered from the waste generated.

The report comes in two forms, a public version and a For Official Use Only (FOUO) version. The public release can be found online however, the FOUO version must be requested from the USALIA. The FOUO version of the report was used to determine solid waste generation rates per person. Using this per unit rate, this report calculates energy and fuel savings. The key findings from the report characterize the solid waste stream. The methodology used by the USALIA included calculations of ratios of waste to determine variance amounts and approximate means, but it does not correlate the results to a real savings value such as fuel or cost savings.

The goal of this research is to directly correlate the waste generated at a contingency base to a reduction in fuel used in the Area of Responsibility (AOR). These fuel savings can then be linked to a reduction of fuel re-supply convoys and casualties associated with convoys. By using the fully burdened cost fuel estimate outlined in Chapter 2, the fuel savings are quantified by cost.

A secondary goal of this research was to determine the extent of the variability in the entire waste stream. If the variability was significant enough, it may be more appropriate to incorporate a WTE system within the waste stream closer to the generating activity, utilizing waste from only one or more activities, rather than at the end of the waste stream utilizing the entire waste stream. Each activity at a base requires different inputs (supplies) and produces different outputs (waste stream), the difference in outputs from one activity to the next can result in higher energy content.

Sample collection by USALIA

Collecting random samples of waste from an installation may be subject to bias, but USALIA took several steps to reduce bias associated with collection efforts. For example, the data collection was done in accordance with a pre-developed Data Collection Plan (DCP) developed by the project team. The DCP was developed in accordance to ASTM Standard D5231-92 with a few modifications that were necessary due to situations that were encountered in the field (U.S. Army Logistics Innovation Agency 2013). The method consisted of collecting a statistically significant number of random samples weighing at least 200 pounds. The samples were then manually sorted into the waste categories outlined by the report (U.S. Army Logistics Innovation Agency 2013). At least 26 samples were collected from each base with the exception of one base where conditions encountered in the field prevented collection of 26 samples.

Data Preparation

The USALIA report used various weights and percentages for the different categories of waste. Because the goal of this research was to quantify operational risk reduced from the energy generated by the waste, the weights of the various waste categories in each sample were the focus of the data analysis. Data were analyzed in two separate computer applications to determine statistical characteristics and to calculate the potential energy content of the waste. In each system, the weight of each waste category was tabulated along with the activity the specific sample represented. The category weight and the originating activity were used in JMP to determine the statistical characteristics of the waste and in Excel to determine the potential energy of the waste and fuel, casualty, and cost reductions.

Variation analysis

The variation analysis portion of this research utilized statistical analysis tools to measure variation in FOB generated solid waste. The data were tabulated in JMP and categorized by base and activity. In order to protect the FOUO elements of the data, the bases were labeled with a letter code (A-E). A snapshot of the raw input data can be seen in Table 2. The analysis was conducted to analyze the median and the variability of the entire waste stream. A fit Y by X plot was created with the waste category on the y-axis and each base on the x-axis. The Wilcoxon rank sums and the Brown-Forsythe tests were applied to the data to determine if the medians of each sample from the separate bases were statistically similar and if the variance between bases could be considered equal. Ordinarily, an analysis of variance would be performed to determine both of these. However, because the samples consist of many points at or near zero, the data are highly skewed and more closely resemble a Chi-square distribution and the approximation of the median is a more appropriate measure of central tendency than the mean, thus warranting the use of Wilcoxon and Brown-Forsythe tests.

Table 2: Weight (lbs) of waste in each sample for JMP analysis

	Base	Sample ID	Corrugated Cardboard	Food Waste	Liquid	Miscellaneous Waste	Mixed Paper	Non-Combustible	Other Combustible	Plastic	Textile	Wood	Sample ID 2	Activity
1	A	1	0	98.3	0	0	29	1	15.4	81.3	0	0	1	DFAC
2	A	2	13.3	11	0	2.2	35	5.4	0	26.2	0	0	2	General
3	A	3	4.6	1.1	0	0	25.7	4.1	40.4	62.1	0	0.3	3	SSA
4	A	4	0	33.6	0	0	25	7.9	15.4	26.8	0	2.3	4	SSA
5	A	5	10.9	7.9	0	24.9	3.5	3.8	0	15.4	0	0	5	General
6	A	6	18.4	1.5	0	0.5	1.2	3.7	0	32	0	0	6	LSA
7	A	7	3.7	1.9	0	0	87.1	0.1	0	0.3	0	0	7	LSA
8	A	8	18.9	37.8	0	8.9	57.1	18.9	0	46.9	6.4	0	8	Motor Pool
9	A	9	5.6	16.2	0	0.4	35.6	2.2	0	21.4	8.5	6.7	9	Admin
10	B	1	9.9	138.9	2.8	0	20.1	17.4	0	27	0	0	1	DFAC
11	B	2	9.8	115.8	8.1	0	34.7	11.8	0	22.9	5.3	1.1	2	DFAC
12	B	3	2.8	0.9	1.7	3.1	16.2	27.6	0	43.6	27	73	3	Motor Pool
13	B	4	14.2	3.7	23.8	0	55	30.5	0	44.4	43	0	4	Motor Pool
14	B	5	29.6	13.9	29.2	0	79.6	16.5	0	42.8	2.5	3.3	5	Motor Pool

Next, the same analysis was performed with each activity, e.g., DFAC, LSA, etc. This was again set up in JMP by analyzing the different activity waste streams to determine if there was a difference from one base to the next. The analysis was performed by creating fit Y by X plots of each waste category by base while excluding all points except one particular source category. For example, a fit Y by X plot was created where all sample points that originated from a source other than DFAC categorized facilities (Administration, LSA, SSA, Motor pool, and general) were temporarily excluded from the data set leaving only waste samples from DFAC sources to be analyzed. This process was repeated until all waste categories and all source categories were plotted. An example output plot is shown in Figure 5; notice also that base D is not included in this analysis due to the nature of the waste collection process at the base. Waste collected from base D was brought to a central point from many different sources and accurate waste generation activities could not be identified for any of the waste present at that particular base.

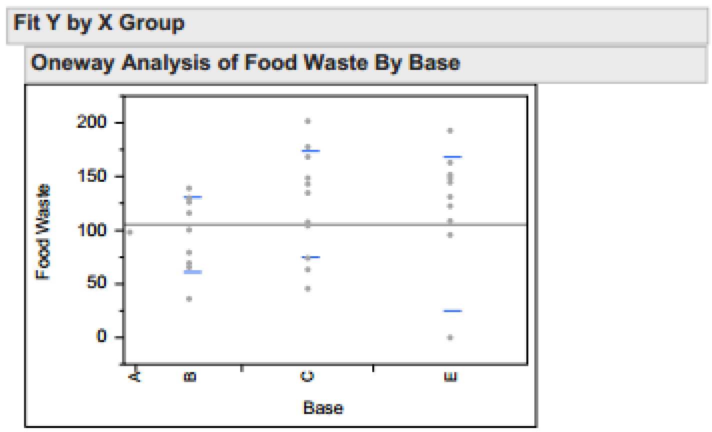


Figure 5: Fit Y by X of Food Waste in DFAC source category

For the comparison of waste in different activities, base D was not included in the analysis because the waste collection process at the base was random in nature and appropriate activities could not be identified. Finding no statistical difference would allow one to make the assumption that all waste from each activity would be similar, regardless of the location or mission of the base. For example, if the Dining Facility (DFAC) waste at each base was statistically similar than it would be logical to assume that DFAC waste at any installation within Afghanistan and Kuwait would have similar energy content for the same size sample.

Energy Output Analysis

The energy output available at each location is completely dependent on the amount and content of the waste available. For the purposes of analysis, it was assumed that the power generation at a typical Air Force location was that of the Harvest Falcon (HF) housekeeping, industrial operations, initial flightline and follow-on flightline kits referenced in Chapter 2. This allowed for the identification of a typical gallon per person reduction when the energy content of the waste was used to supplement power production, which is the basis for the reduction of risk. In reality, the power production equipment can fluctuate based on encountered difficulties in the field. But for the purposes of this research, it was assumed the combination of HF power production assets above was the power requirement needed to supply 1,100 personnel with adequate power needs. Power output and consumption rates for a HF set for 1,100 people was then calculated on a per person basis to facilitate a calculation of potential power from the waste stream on a per person basis. As a baseline value of power production requirements, the HF power production output in Kilowatt hours (kWh) and fuel requirements was used. The HF asset produces 61,500 kWh of electricity daily and consumes 4,880 gallons of fuel (SERDP 2010). According to Air Force planning documents (Department of the Air Force 2008); this particular HF set up is designed to maintain a population of 1,100 people. By dividing the generator output in kWh by the gallons of fuel used the generator conversion rate can be calculated as 12.6 kWh per gallon of fuel consumed. Dividing this number by the amount of people the set is designed for results in a baseline value of 0.011 kWh/gal per person.

In order to evaluate the waste stream energy content on a per person basis, a population value was generated for the waste presented in the CBWSA. For this research it was sufficient to assume that the total weight of waste from each base could be divided by the number of days that samples were taken and further divided by the waste generation per person per day calculated by the CBWSA report. Equation 1 below shows this calculation. The equation was solved for each base and the values were aggregated to produce an estimated population that produced the samples. The total population number was then used to determine how much energy content was available in the waste per person.

Equation 1

$$\begin{aligned} \textit{Sample population} \\ &= (\textit{sample weight})/(\textit{number of days}) \\ &\quad /(\textit{waste gen per person}) \end{aligned}$$

After the baseline values from the HF set was established, the research required a rate per person for the entire waste stream and the individual activities. This analysis consisted of an evaluation in excel to determine the energy content of each sample. The energy content in million British Thermal Units (MMBTUs) of each waste category was used in combination with the median values of waste for a "typical" sample these values can be seen in Table 3 below. Based on the predominant plastic wastes of PET, HDPE, and LDPE/LLDPE, an average of these energy contents was used for the energy content of plastic.

Average moisture content was combined with the weight of each waste category to determine the heat content of a typical sample on a dry weight basis. The average percent moisture content for each waste category is presented in Table 4.

Table 3: Energy content of waste categories (USALIA 2013)

Category		Heat Content (MMBtu/dry ton)
Corrugated Cardboard		17
Food Waste		13
Liquid		0
Miscellaneous Waste		20
Mixed Paper		7
Non-Combustible	Ferrous Metal	0
	Non-Ferrous Metal	0
	Glass	0
Other Combustible		27
Plastic	#1- PET	21
	#2 – HDPE	19
	#3 – PVC	17
	#4 - LDPE/LLDPE	24
	#5 – PP	38
	#6 – PS	36
	#7 – other	21
Textile		14
Wood		10

Risk Analysis

A major risk of contingency operations is the loss of people or assets during fuel re-supply missions. Any amount of fuel savings at the point of use could be directly related to the reduction of risk for casualties experienced on re-supply convoy operations. The energy output results from the previous step were used in combination with the HF fuel requirements to determine the number of fuel re-supply convoys and casualties that could be avoided. According to the Sustain the Mission Project (Eady et al. 2009), in

Table 4: Moisture content for waste categories (USALIA 2013)

Waste Component		Average Field Measurement
Corrugated Cardboard		12.6
Food Waste		53.6
Liquid		100.0
Miscellaneous Waste		57.8
Mixed Paper		34.1
Non-Combustible	Ferrous Metal	0.0
	Non-Ferrous Metal	1.3
	Glass	0.0
Other Combustible		6.4
Plastic	#1- PET	0.0
	#2 - HDPE	9.6
	#3 - PVC	6.7
	#4 - LDPE/ LLDPE	14.4
	#5 - PP	0.0
	#6 - PS	7.2
	#7 - Other	1.6
Textile		21.9
Wood		7.9

2007 there was 897 convoys of fuel sent to Afghanistan with an average of 97,818 gallons of fuel per convoy and one death for approximately every 23.6 convoys. These numbers were used to estimate the number of convoys and casualties that could be avoided based on the conversion of waste produced by 1,100 military personnel over a two year period. Like the previous analysis, this analysis was conducted with a maximum and a realistic case.

Variance and Failure Threshold

For this analysis, the IQR for each of the categories was used to determine a failure point for parts of the waste stream based on expected energy content. The lower limits of the IQR were used to determine the lower limit of the expected energy output from waste. The samples taken by the USALIA were approximately 200 lbs each, and a direct comparison could not be made from a typical sample to the energy generated by a gallon of fuel. Instead, the weight of one gallon of fuel and all fuel used to transport one gallon of fuel to the point of use were used as a comparison mark. According to the fully burdened cost of fuel discussion presented in Chapter 2, it takes anywhere from 4 to 6 gallons to transport one gallon to the point of use. Using the weight of diesel of 7.5 pounds per gallon (Walker 2007) it stands that it takes a minimum of 37.5 pounds (5 gallons times 7.5 pounds per gallon) of fuel to produce the 12.6 kWh/gallon of energy produced by the generator sets of the Harvest Falcon asset. Using the lower limits of the IQR for each category a comparison was made to determine if 37.5 pounds of waste could produce the same 12.6 kWh of energy. In order for WTE to be considered for use over fuel for power production purposes it would need to outperform fuel. Because weight is a major consideration when shipping anything to the AOR it stands to reason that weight would be an accurate consideration when discussing success/failure criteria for new technologies. For WTE to be considered more desirable than fuel, 37.5 pounds of waste would need to produce at least 12.6 kWh of energy.

Decision Model Development

The final goal of this research was to develop a decision model to be used by decision-makers during stable (sustained) base operations. The goal of the model was to incorporate the waste characteristics with known decision factors for WTE. The waste characterization data was used as the primary criteria for formulating the decision tree. The decision tree was limited to only the variables that were outlined by the data (amount and variability of the waste, whether or not partitioning would be recommended, and what the primary waste component was) and these variables became the key factors in the decision process. The amount and variability were treated as chance events, where the results were either high or low. The high and low amount and variability lead further into the diagram to whether or not the waste stream could be partitioned. Lastly, the question of what primary waste component was present served to further delineate between technologies. For this portion it was decided to determine if the waste was primarily organic matter (e.g., food waste) or synthetic (e.g., plastics).

IV. Analysis and Results

Chapter Overview

The results of the analysis attempt to answer the questions presented in the previous chapters. The order of the chapter follows the logical order that was necessary to make assumptions for latter parts of the analysis.

Statistical Analysis

The waste data provided by the United States Army Logistics Innovation Agency (USALIA) were broken out into categories of corrugated cardboard, food waste, liquid, miscellaneous, mixed paper, non-combustible, other combustible, plastic, textile, and wood. The source locations of each of the samples was also noted during the study and categorized as one of the following activities: Administrative, Dining Facility (DFAC), General, Life Support Area (LSA), Motor Pool, and Supply Support Activity (SSA).

In order for the analysis to be applied to locations other than the five bases in the report, it was necessary to determine if waste across the five bases was similar. If the waste generated at the five separate locations were considered statistically similar, then it could be further inferred that waste at any location would also be similar.

Statistical plots of the results of each individual test can be seen in Appendix A. Using an alpha of 0.05 for each of the tests, each category of waste was evaluated and found to either have similar waste values and variances or not. This analysis was conducted for each of the ten categories of waste.

Waste Stream as a Whole

To determine if median values of waste can be expected to be similar from one location to the next, an analysis of the total waste stream was required. When all of the waste was evaluated as a whole, four waste categories failed either the Wilcoxon's rank sums or Brown-Forsythe test for similar medians or constant variance. The mixed paper category was one of two categories to fail both the Wilcoxon and the Brown-Forsythe test. This indicates that mixed paper levels could potentially differ greatly from one location to the next. This could be a result of the mission at the base or possibly the branch of service the base primarily supports. Further research would be necessary to determine why the variability and medians were so different from one base to the next. Three categories, liquid, plastic, and textile, all failed the Wilcoxon test indicating that the sample medians were not equal from one base to the next. The p-values for the total waste stream are shown in Table 5 below where all values under 0.05 have been highlighted.

Table 5: P-values for total waste stream

	Corrugated Cardboard	Food Waste	Liquid	Miscellaneous Waste	Mixed Paper
Wilcoxon	0.0689	0.3232	0.0002	0.3355	0.0011
Brown-Forsythe	0.498	0.4746	0.2422	0.1852	0.0203
	Non-Combustible	Other Combustible	Plastic	Textile	Wood
Wilcoxon	0.1688	0.6185	0.0001	0.0023	0.1915
Brown-Forsythe	0.4207	0.1001	0.1667	0.4965	0.1429

In the report from USALIA liquid represented liquid left over from drinking bottles and for most waste to energy processes, liquid is not a desired component and the fact that the median value cannot be expected to be similar from base to base is not necessary good or bad in any way. One of the goals of the USAF Energy Strategic plan is to "foster an energy aware culture". Part of that culture will inevitably be the source segregation of waste and elimination of liquid from the waste stream whenever possible. Plastic, however, has one of the highest energy contents of all the waste and is relied upon by some WTE systems. If plastic waste cannot be accurately estimated, it could cause problems while implementing certain technologies as some technologies specifically rely on plastic waste components to generate energy.

Activity Specific Waste

The analysis of the overall characteristics of the waste stream can determine what amount of energy would be typical for a contingency. However, without knowing the specific requirements of the WTE system to be used, it might be more beneficial to determine if certain activities generated a more stable waste stream/energy supply. The WTE technology to be chosen is highly dependent on the available waste, which itself is dependent on the generating activity. The report provided by the USALIA categorizes the waste source into six categories; it then becomes logical to determine if the generating categories can be assumed to be consistent from location to location.

These two types of analysis provide the basis for making the assumption that the median amounts of waste in each category are consistent throughout the countries. P-values were calculated for each of the waste categories. There was only one case in which a particular category failed both the Wilcoxon and Brown-Forsythe tests. This occurred with the liquid category for DFAC waste. The results for this analysis illustrate which areas of the waste stream can be relied upon to be statistically similar. There are two categories of waste that show statistical similarity in each activity, unfortunately the two categories are non-combustible and miscellaneous waste. Non-combustible waste cannot be used in WTE because of the lack of energy content and miscellaneous waste is generally made up of items that are unsuitable for standard sorting and/or waste treatment methods (U.S. Army Logistics Innovation Agency 2013). Further, the non-combustible waste may be better suited for other roles including recycling (glass, metal) or construction filling materials (rocks, concrete, dirt, etc.)

One category that experienced very little variation across activities and bases was corrugated cardboard. Corrugated cardboard can be considered statistically similar in nearly all activities. The heat content of cardboard is high enough to justify using it for many WTE processes therefore the relative expected stability of the waste can benefit the development process of certain systems. The associated p-values can be viewed in Table 6. The analysis based on activity generation suggests that a portion of the variability can be avoided by incorporating WTE systems that target specific waste generated by specific waste streams. By implementing technology, designed to specifically target or avoid certain types of waste, within the waste stream instead of at the end, systems could generate a higher output and experience less incompatible waste components. After the statistical analysis, the median amounts of waste were then used to calculate a typical energy output for waste generated at a contingency base and, in turn, determine a potential number of convoy, casualty, and cost reductions that can be expected with the installation of WTE at a contingency base.

Table 6: P-values for waste based on activity generation point

		Corrugated Cardboard	Food Waste	Liquid	Miscellaneous Waste	Mixed Paper
Admin	Wilcoxon	0.0937	0.3899	0.4459	0.8592	0.584
	Brown-Forsythe	0.6367	0.6441	0.2593	0.8402	0.7483
DFAC	Wilcoxon	0.3907	0.5549	0.0052	0.4272	0.0208
	Brown-Forsythe	0.0502	0.2363	0.0941	0.2711	0.2923
General	Wilcoxon	0.0912	0.3397	0.1781	0.4261	0.1775
	Brown-Forsythe	0.0746	0.8212	0.1436	0.613	0.2783
LSA	Wilcoxon	0.2543	0.2194	0.1888	0.1107	0.1133
	Brown-Forsythe	0.4699	0.0755	0.5316	0.4264	0.0967
Motor Pool	Wilcoxon	0.9411	0.0715	0.057	0.1699	0.1349
	Brown-Forsythe	0.5624	0.0057	0.0005	0.5611	0.2733
SSA	Wilcoxon	0.1614	0.1561	0.4402	0.4402	0.2021
	Brown-Forsythe	0.0004	0.0001	0.5286	0.4068	0.0001

		Non-Combustible	Other Combustible	Plastic	Textile	Wood
Admin	Wilcoxon	0.5377	0.2123	0.3815	0.2754	0.6065
	Brown-Forsythe	0.164	0.0003	0.689	0.0157	0.6719
DFAC	Wilcoxon	0.4072	0.0011	0.0007	0.0301	0.8478
	Brown-Forsythe	0.5765	0.3798	0.0364	0.069	0.0596
General	Wilcoxon	0.4684	0.4618	0.1681	0.1753	0.1045
	Brown-Forsythe	0.9002	0.0067	0.6444	0.0001	0.7515
LSA	Wilcoxon	0.5375	0.7118	0.4635	0.1179	0.033
	Brown-Forsythe	0.8034	0.8686	0.8928	0.4195	0.5671
Motor Pool	Wilcoxon	0.1044	0.2213	0.017	0.2651	0.4713
	Brown-Forsythe	0.1342	0.5782	0.7811	0.5934	0.0054
SSA	Wilcoxon	0.2021	0.0581	0.3447	0.2109	0.0337
	Brown-Forsythe	0.3889	0.2099	0.1041	0.1234	0.5084

Energy Output Analysis

For the first analysis, all waste categories were left in the analysis even those who failed the statistical tests previously mentioned. The median values from each waste category were used in combination with the moisture content and heat content to calculate a potential energy of a sample originating from the designated activity area. This illustrates a maximum potential value for each sample. The results for this analysis are presented in Figure 6.

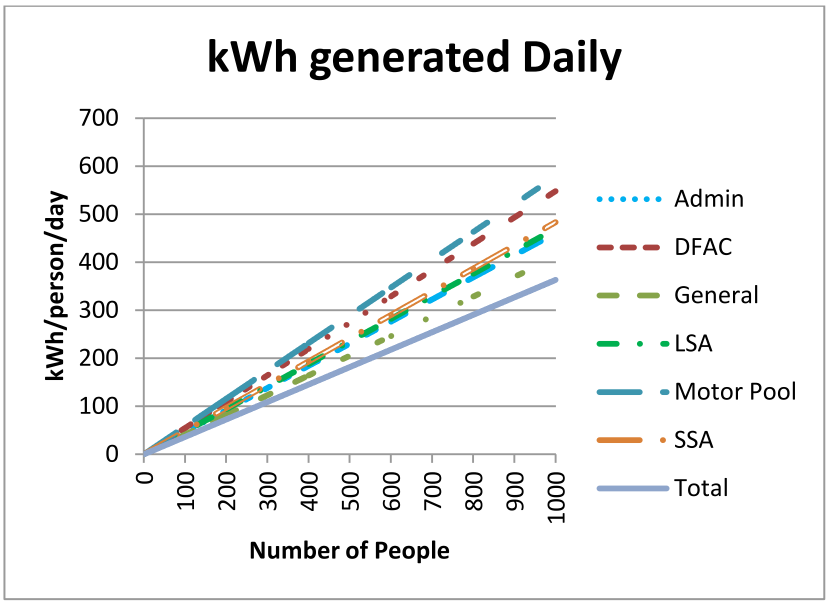


Figure 6: Maximum energy potential

The chart illustrates that waste collected from the motor pool and DFAC areas has the highest potential energy with the total waste stream having the lowest energy content per sample. This is significant because it indicates that the heat content gets diluted as the waste stream grows in complexity.

The results outlined above provide an example of the potential of the waste stream, if 100% of the waste were converted into energy. In reality, that would not be the case. To illustrate a more realistic scenario, in an effort to account for conversion efficiency related issues, another analysis was completed using only 80% of the available energy content. This percentage was arbitrarily chosen because each WTE system has a different efficiency and 80% illustrates the bulk of the potential energy available for conversion. Another factor that was taken into consideration was all waste categories that did not pass either the Wilcoxon rank sum or the Brown-Forsythe tests. Any category that failed either or both of the tests may not have similar volumes from location to location and, therefore, they cannot be counted on as a constant source. For the second analysis, all categories that failed either of the tests were not included in the calculation. Figure 7 illustrates the energy results of this analysis. Results indicate that the variance that is experienced by Motor Pool, SSA, and the total waste streams is significant enough to drastically reduce the expected energy content of a typical sample. It also indicates that the variance of the remaining categories does not significantly reduce the available energy content.

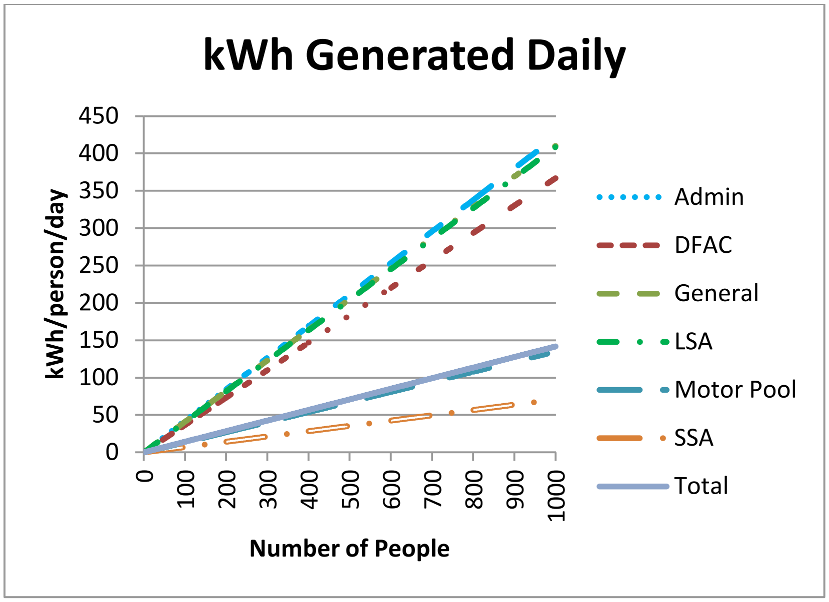


Figure 7: Energy potential without statistically dissimilar categories

Variance and Failure Threshold

The results from this analysis illustrate that 4 of the 7 different categories examined pass the test. Motor Pool and SSA waste streams failed the test which is not surprising due to the variability in the waste data. The total waste stream also failed the test due to the dilution effect of the rest of the waste activities. This indicates that the energy content from motor pool and SSA wastes do not produce enough energy to be used as a viable source of energy. It also indicates that these two waste streams are responsible for the lack of energy in the total waste stream. The results can be seen in the following table and detailed IQR results can be found in Appendix B. These results illustrate that if Motor Pool and SSA specific wastes or the total waste stream drops below the expected threshold, then the energy content of waste may be too low to utilize it for WTE processes. This helps to illustrate which areas of the waste stream have a consistently higher energy potential.

Table 7: Failure Threshold upper and lower limits of IQR

IQR	Activity	kWh/37.5 #
High	Admin	69.38
Low	Admin	18.20
High	DFAC	63.79
Low	DFAC	21.38
High	General	80.14
Low	General	19.77
High	LSA	62.83
Low	LSA	14.25
High	Motor Pool	92.79
Low	Motor Pool	11.44
High	SSA	93.78
Low	SSA	8.30
High	Total	72.53
Low	Total	10.24

Risk-Based Analysis

Figures 8 and 9 illustrate that the number of convoys that could be avoided by converting the waste generated by 1,100 people over a two year period could be as high as 100 convoys if all waste was converted to energy. These results are significant especially when the total number of deployed forces is considered. Each instance shows a maximum case and a minimum case. The maximum case includes all of the data regardless of the statistical uncertainty of the waste category and the minimum case does not include any waste category that failed either the Wilcoxon's rank sum or the Brown-Forsythe tests.

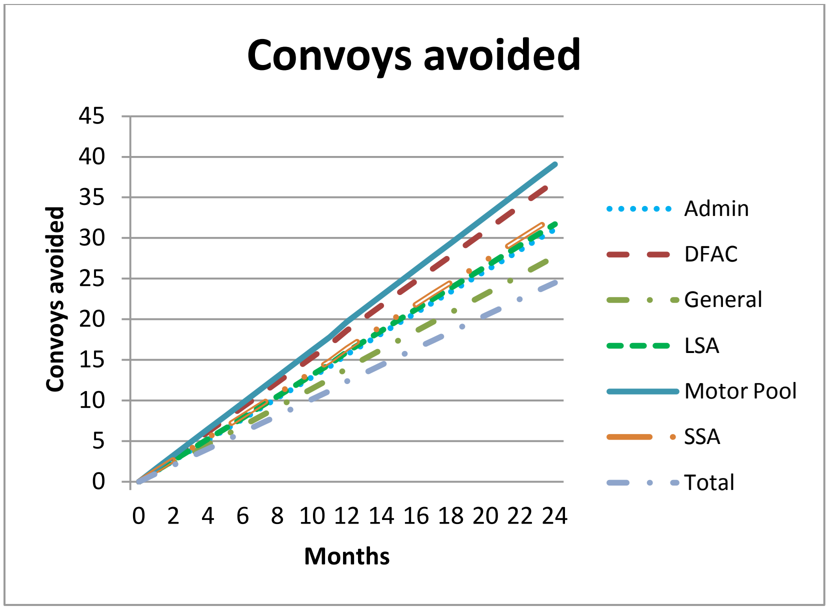


Figure 8: Convoys avoided by 1,100 personnel over time

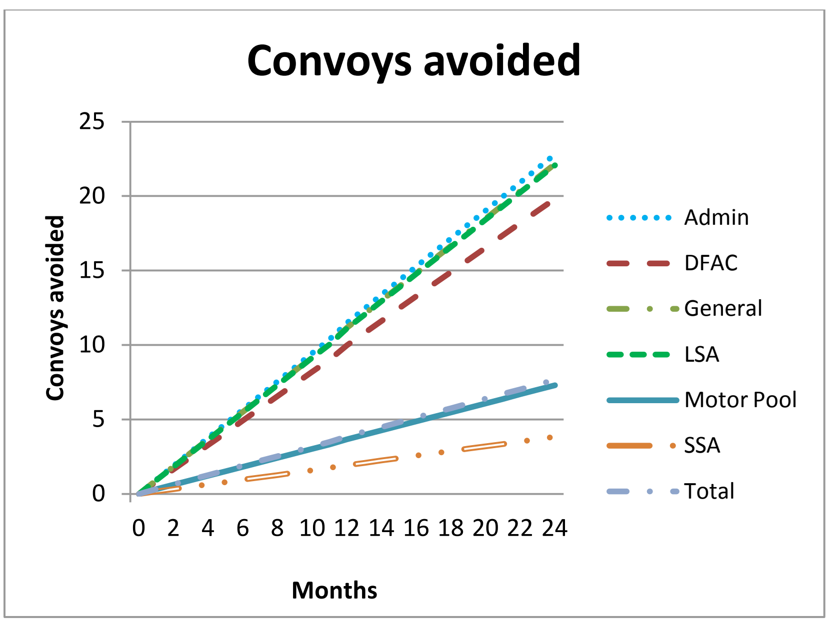


Figure 9: Convoys avoided by 1,100 personnel over time without dissimilar categories

Each convoy is unfortunately associated with a number of deaths, so it follows that if the number of convoys is reduced then the number of deaths will also be reduced.

The expected casualties reduced by converting waste generated by 1,100 people could be as high as 9 in a two year period. This number can be expected to increase if solid waste generated by the total deployed force was converted to energy. The minimum case for this analysis illustrates a casualty reduction of approximately 4 personnel over a two year period. If risk is considered to be the primary driver for the use of WTE at a contingency location, then the reduction of casualties possible makes a strong case for the United States military to implement WTE at contingency locations. The results from Figures 10 and 11 are based off of the assumptions made from this report and that of the Sustain the Mission Project (Eady et al. 2009) and assume an average amount of casualties in 2009 and may not be representative of today's fuel convoys. The true correlation is most likely not linear, but by converting waste to energy at contingency bases, fuel savings will occur which will lead to a decrease in casualties.

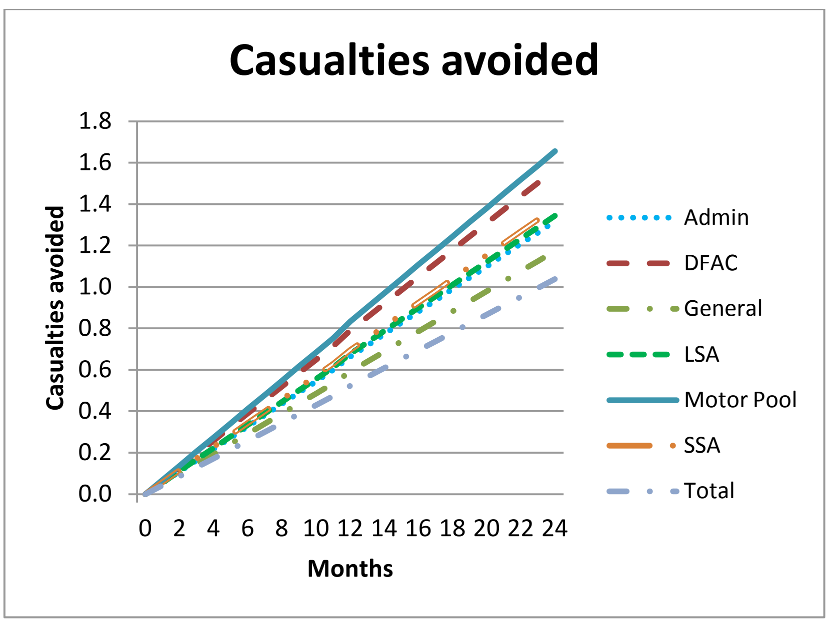


Figure 10: Maximum casualties avoided over time

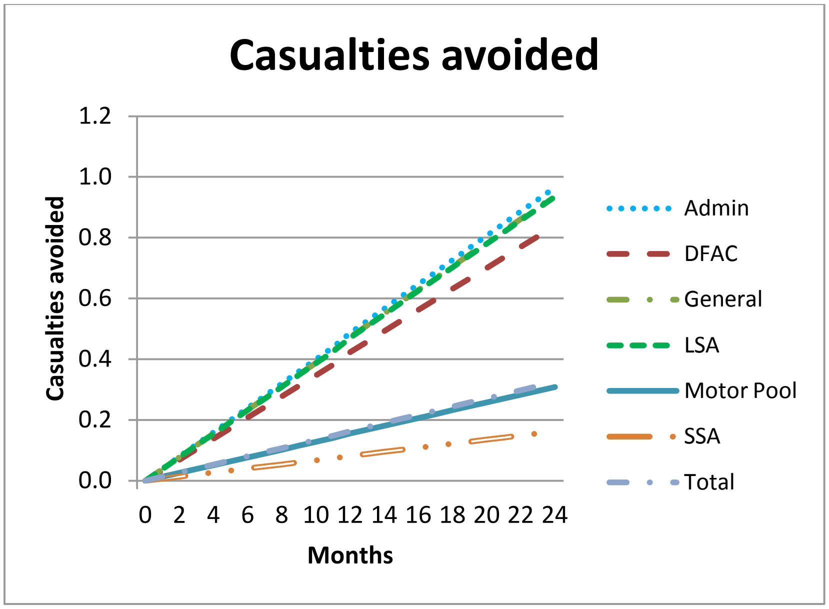


Figure 11: Casualties avoided over time without dissimilar categories

Cost Analysis

The main purpose of this report is to illustrate the reduction in risk that is possible with the implementation of WTE. However, cost does play a role in any decision made by the DoD. In the case of a deployed environment, it is understood that risk reduction takes precedence and cost is secondary. Due to this fact, the cost analysis for this research is basic in nature and should not be relied on as a planning factor. Though cost is not specifically the goal of this research, the combination of calculations for the amount of fuel saved and the fully burdened fuel cost is a simple way to illustrate the potential of waste to energy. Although risk avoided due to installation of WTE should be enough for decision makers to seriously consider WTE, the illustrations in Figure 12 below help to solidify the case. The fully burdened cost of fuel presented previously alludes to the fact that the cost of fuel used at the point source in the AOR can be very difficult to determine exactly. The results illustrate a significant cost saving available in the waste stream generated by only 1000 troops. In the current atmosphere of budget cuts and involuntary separations, the amount of funding that is literally being thrown away is staggering and investment to recover some of the cost is imperative.

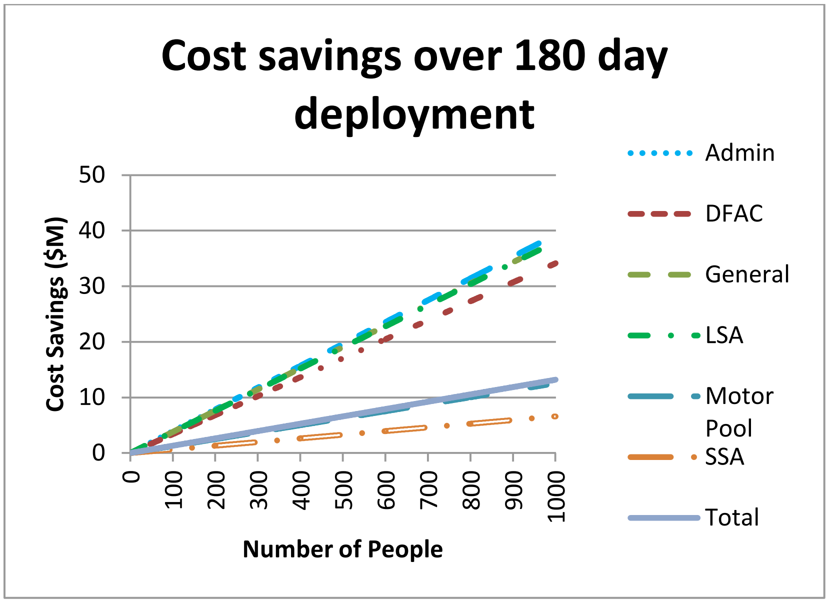


Figure 12: Cost savings without dissimilar waste at $78 per gallon

Decision Model

The current technologies being put into use vary greatly and it is very difficult to point to any one specific technology based on the waste characteristics alone. This is partly because current visions for WTE implementation in the AOR are for systems that can handle any variation of Municipal Solid Waste (MSW). Each technology has a specific type of waste that it may work better with, but most are not necessarily optimized for any one specific waste, with a few exceptions. In cases where the amount of waste is increasing to a nearly unmanageable level, technologies such as incineration, gasification, or pyrolysis may be beneficial. These systems can achieve very high volume reduction rates and any energy recovered could be considered an additional benefit. If a waste study is conducted by personnel in the field, and the study produces a wide variety of waste, then steps may need to be taken to sort the waste stream and analyze separate parts to determine a potential viable WTE source. For locations that are great distances away from central transportation hubs, the initial cost and transportation of a waste system will be less important. This will open up the range of available technologies and provide personnel with the ability to select a system that will handle their greatest value wastes. Conversely, if the location is closer to a transportation hub, then the cost benefit ratio of the technology will be more important. The closer location pays less for fuel at the fully burdened cost and, therefore, increases the payback time of any technology they choose. Available footprint at a base will also be a predetermining factor; if the footprint available is small, then any system that requires a significant amount of pretreatment would need to be avoided. The variability calculations conducted in this research use the IQR to determine a failure point for WTE. The failure point is a situation in which the performance of the energy from waste does not meet the current electricity production rate of fuel. If the waste stream that is available for the conversion process fails to meet this minimum requirement it may not be worth pursuing WTE in the first place. Overall the selection of a system is highly dependent upon many factors and not just the waste alone and until more off-the-shelf systems are developed, a true decision model that will encompass all the different technologies may not be feasible.

A decision tree was created that can provide some broad criteria for selecting WTE at a contingency location. The decision tree was created by a pure analysis of the data alone and thus it tries to identify how four key areas can affect the decision. The four key areas are the amount and variability of the waste, whether or not the waste stream can be partitioned, and whether the main component of the waste stream (or part of the stream if it was partitioned) is organic (food waste) or inorganic (plastics, cardboard, etc.). The decision tree presented below addresses these questions to identify potential technologies. In the diagram, boxes represent areas where a choice is made and circles represent a possible outcome based on the specific waste stream. The conclusions point to anaerobic digestion, pyrolysis, gasification, or incineration. Incineration, pyrolysis, and gasification can all achieve significant volume reduction and anaerobic digestion is primarily used for processing organic wastes. Table 8 outlines the directions for using the decision tree in Figure 13.

Table 8: Decision tree key

Decision tree node	Description
A	Refer to failure threshold analysis to answer this question
B	Based off of average tons per day produced at location
C	Refer to variation analysis to determine level of variability
D	Refer to statistical analysis section to determine if partitioning the waste stream would be recommended
E	Based on waste composition study

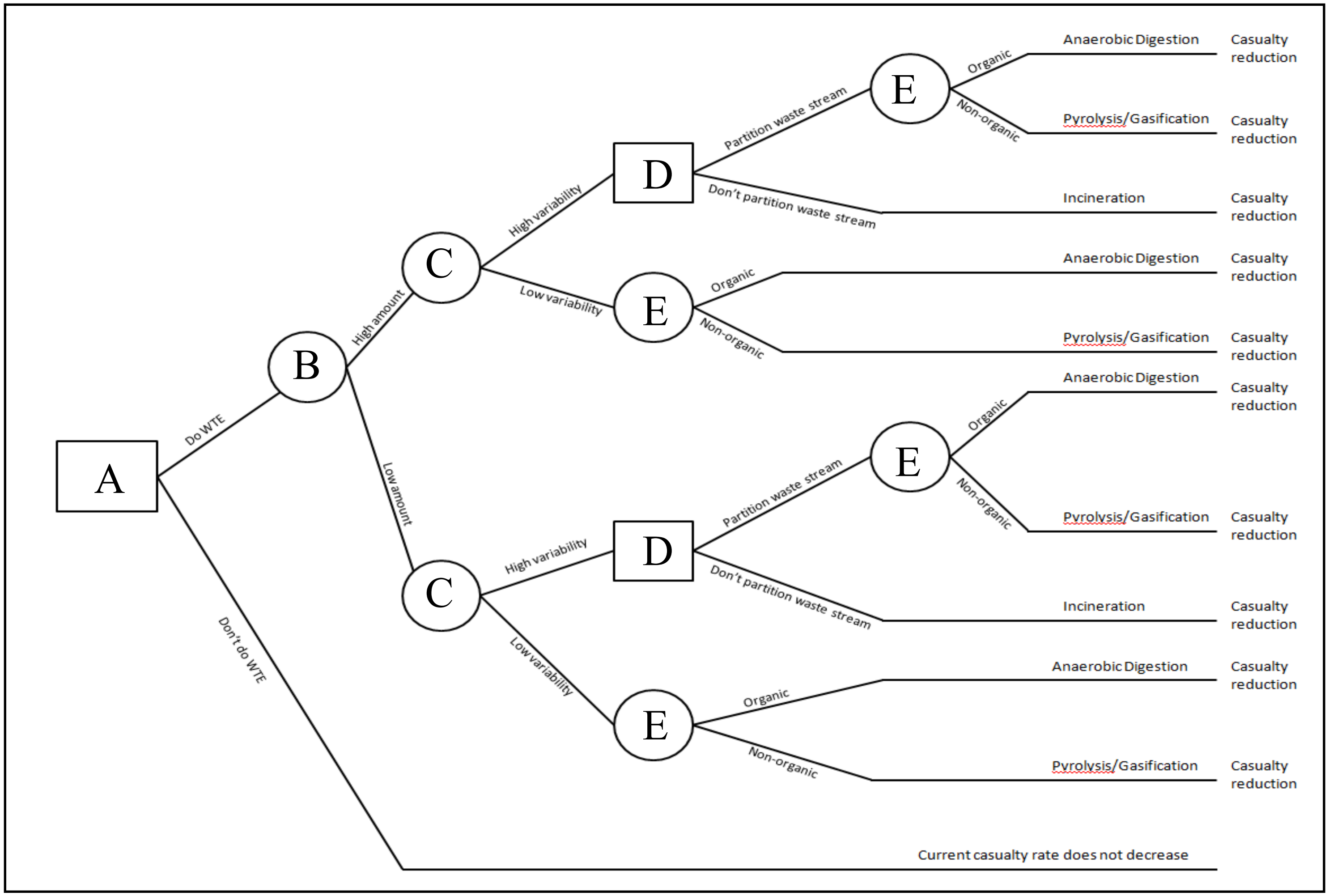


Figure 13: Decision tree diagram

V. Conclusions and Recommendation

Chapter Overview

This chapter summarizes the importance of waste characterization, fully burdened costs of fuel, and risk in the contingency environment. The significance of the research is discussed. Future research is also identified to build upon the results from this research. It describes the approach utilized by the research in answering the investigative questions below:

1. How does waste stream variation compare at the five locations?
2. How can we consistently quantify risk based on WTE opportunities?
3. What decision elements should be included in a WTE decision model?

Significance of Research

This research supports the incorporation of WTE systems at forward operating bases where the waste streams experience less variation and operational risks are much higher. By using a different analysis than that used in the CBWSA, this research draws conclusions similar to the report and has also produced a "typical" sample that can be expected. The amount of waste generated at any given installation will likely be similar to that used in this research. If waste is similar from one installation to the next, then the focus in system design can be utilized for modularization and differing capacity ratings rather than adjustments to waste stream values. Less expensive systems can be designed to handle a lower variability of waste by isolating certain generating activities rather than focusing on the entire waste stream. The case for WTE is not simply based on the cost benefit ratio, as it also takes the lives of the deployed soldiers into account. The fact that the conversion of waste could potentially save dozens of lives per year makes it more justified. The combined use of waste characterization, comprehensive fuel accounting, and risk analysis, can save both money and human lives. It is important that waste streams be properly characterized before any selection is made as the types of waste can have drastic effects on the type of WTE technology that is chosen. Convoy operations for fuel re-supply can be extremely dangerous and should be reduced as much as possible. By implementing WTE from the planning stage, the military could reduce operational risk when establishing new campaigns in other countries.

Based on the results of the calculations, it appears that waste is not significantly different from one location to the next. This is significant for system designers because the consideration for a highly variable waste stream will not need to take priority when systems are created. According to the calculations, if all waste was converted to energy, the number of convoys and casualties reduced in a six month period would be over 40 and 2, respectively. These results only account for the waste generated by 1,000 people. If the waste of all deployed forces were converted to energy, the numbers would be much higher.

Recommendations for Future Research

Some of the assumptions made for this research were intended to provide scope for the research and allow for a general overall analysis of waste potential in the AOR. An analysis of specific power production assets and electrical grid properties for an individual base would allow a researcher to more accurately determine what potential energy is available in a particular base's waste stream. This would include an analysis of the power output from generators used at a base to provide power to an existing distribution system. Values obtained from such research would replace the Harvest Falcon asset assumption and give a more accurate measure of energy. If this could be accomplished for multiple bases, the results could be aggregated to determine whether or not the kWh/person ratings are similar from one base to another.

Each system is designed with different aspects and considerations such as conversion factors and waste needs. By analyzing current and future off-the-shelf technologies and incorporating specific details of the design into this research, it would allow a researcher to compile the potential energy for each system. This would help planners determine which types of energy conversion technologies generate higher values for waste from a contingency base.

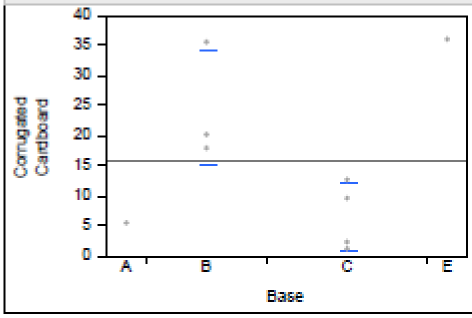
When more off-the-shelf technologies are developed, a comprehensive analysis should be conducted to illustrate key factors associated with each system. This can be incorporated into the decision tree to identify specific technologies that may be suited for each situation. Combining the output values and waste requirements of different systems will refine the decision model. The model can also be further refined by incorporating other key consideration factors.

An analysis of waste generation habits at contingency locations, focusing on why and how certain types of waste are generated in each activity, could provide recommendations that could be instituted on the unit level to ensure an adequate amount of energy is available in the waste stream. If the variance of the waste stream can be kept to a minimum, it would ensure a sufficient amount of energy is always present in the waste stream. This can be accomplished by approaching the waste stream using six sigma principles, where a defect can be defined as an unwanted piece of waste. By using six sigma principles to reduce or eliminate unwanted waste in a specific waste stream, it would provide a higher quality waste stream for the WTE process. This study could analyze the inputs and outputs of various activities on a contingency base to determine ideal opportunities to reduce variability in the waste stream.

Appendix A

Fit Y by X Group

Oneway Analysis of Corrugated Cardboard By Base



Excluded Rows 117

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	3.000	5.000	3.00000	-0.581
B	3	21.000	15.000	7.00000	1.420
C	4	12.000	20.000	3.00000	-1.837
E	1	9.000	5.000	9.00000	1.356

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
6.4000	3	0.0937

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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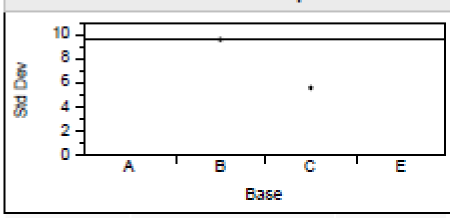
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.000000	0.000000
B	3	9.589578	7.333333	6.600000
C	4	5.590766	4.700000	4.700000
E	1	.	0.000000	0.000000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.0570	1	5	[illegible]510
Brown-Forsythe	0.2525	1	5	0.6367
Levene	2.1230	1	5	0.2049
Bartlett	0.5911	1	.	0.4420

Warning: Small sample sizes. Use Caution.

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> .05 so variance is =

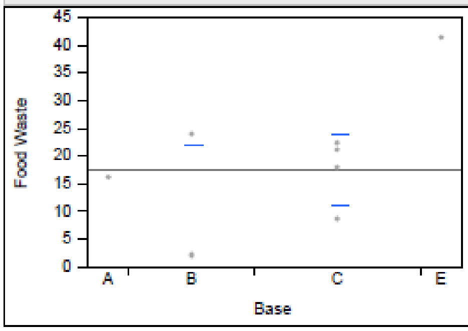
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
8.4696	1	3.0189	0.0615

Fit Y by X Group

Oneway Analysis of Food Waste By Base



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Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	4.000	5.000	4.00000	-0.194
B	3	11.000	15.000	3.66667	-0.904
C	4	21.000	20.000	5.25000	0.122
E	1	9.000	5.000	9.00000	1.356

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
3.0111	3	0.3899

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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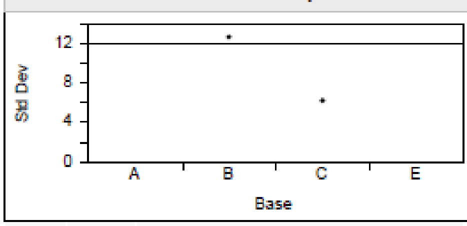
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.000000	0.000000
B	3	12.61600	9.711111	7.433333
C	4	6.20128	4.437500	4.225000
E	1	.	0.000000	0.000000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.3081	1	5	0.3045
Brown-Forsythe	0.2413	1	5	0.6441
Levene	3.3103	1	5	0.1285
Bartlett	1.0124	1	.	0.3143

Warning: Small sample sizes. Use Caution.

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> .05 so variance is =

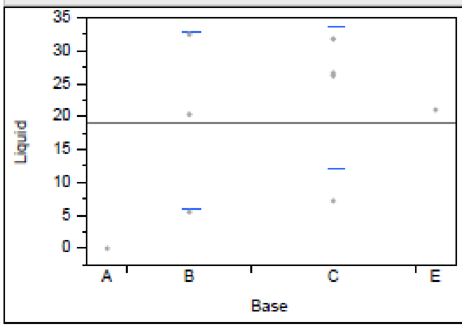
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
1.0577	1	2.7307	0.3861

Fit Y by X Group

Oneway Analysis of Liquid By Base



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Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	1.000	5.000	1.00000	-1.356
B	3	15.000	15.000	5.00000	0.000
C	4	24.000	20.000	6.00000	0.857
E	1	5.000	5.000	5.00000	0.000

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
2.6667	3	0.4459

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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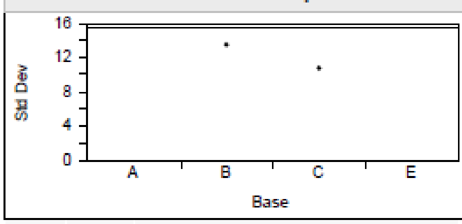
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.000000	0.00000
B	3	13.52085	9.288889	13.06667
C	4	10.80540	7.875000	6.25000
E	1	.	0.000000	0.00000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.1729	1	5	[illegible]948
Brown-Forsythe	1.6182	1	5	0.2593
Levene	0.0820	1	5	0.7861
Bartlett	0.1018	1	.	0.7497

Warning: Small sample sizes. Use Caution.

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> .05 so variance is =

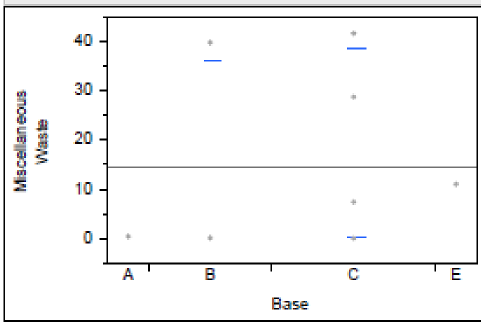
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.1372	1	3.7945	0.7308

Fit Y by X Group

Oneway Analysis of Miscellaneous Waste By Base



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Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	4.000	5.000	4.00000	-0.194
B	3	12.500	15.000	4.16667	-0.519
C	4	22.500	20.000	5.62500	0.492
E	1	6.000	5.000	6.00000	0.194

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
0.7591	3	0.8592

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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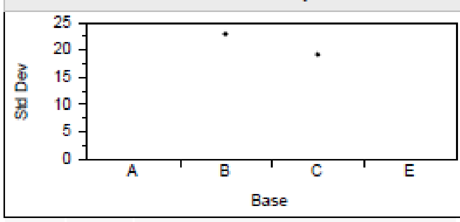
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.00000	0.00000
B	3	22.94973	17.66667	13.30000
C	4	19.20059	15.77500	15.77500
E	1	.	0.00000	0.00000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.1720	1	5	[illegible]955
Brown-Forsythe	0.0451	1	5	0.8402
Levene	0.1347	1	5	0.7286
Bartlett	0.0642	1	.	0.7999

Warning: Small sample sizes. Use Caution.

damack
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> .05 so variance is =

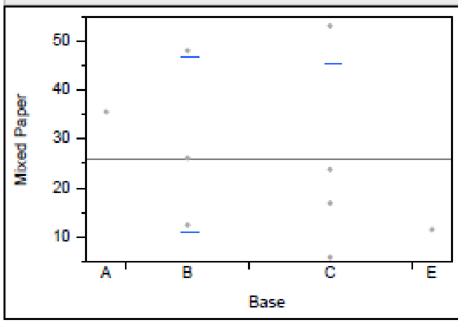
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.1424	1	3.9292	0.7254

Fit Y by X Group

Oneway Analysis of Mixed Paper By Base



Excluded Rows 117

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	7.000	5.000	7.00000	0.581
B	3	17.000	15.000	5.66667	0.387
C	4	19.000	20.000	4.75000	-0.122
E	1	2.000	5.000	2.00000	-0.968

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
1.9444	3	0.5840

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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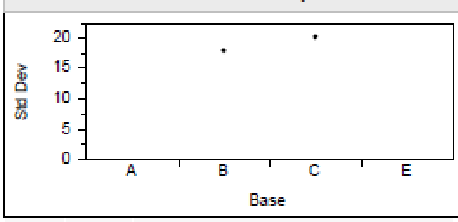
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.00000	0.00000
B	3	18.01009	12.82222	16.46667
C	4	20.25593	14.13750	13.57500
E	1	.	0.00000	0.00000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.0433	1	5	0.[illegible]433
Brown-Forsythe	0.1150	1	5	0.7483
Levene	0.0253	1	5	0.8799
Bartlett	0.0269	1	.	0.8698

Warning: Small sample sizes. Use Caution.

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> .05 so variance is =

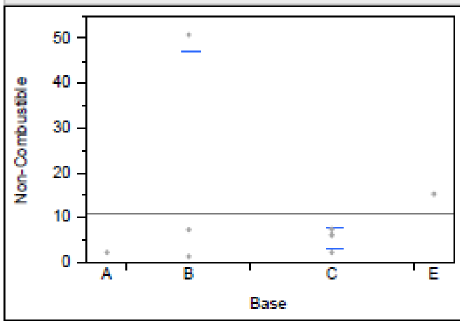
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.0737	1	4.7467	0.7974

Fit Y by X Group

Oneway Analysis of Non-Combustible By Base



Excluded Rows 117

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	2.500	5.000	2.50000	-0.778
B	3	16.000	15.000	5.33333	0.130
C	4	18.500	20.000	4.62500	-0.246
E	1	8.000	5.000	8.00000	0.972

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
2.1709	3	0.5377

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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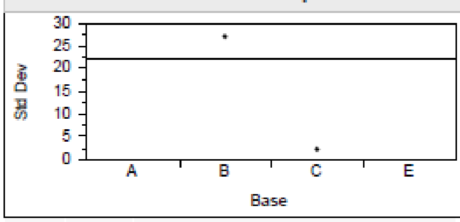
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.00000	0.00000
B	3	27.07126	20.71111	18.53333
C	4	2.25315	1.62500	1.35000
E	1	.	0.00000	0.00000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.5044	1	5	[illegible]744
Brown-Forsythe	2.6581	1	5	0.1640
Levene	17.0136	1	5	0.0091 *
Bartlett	8.5765	1	.	0.0034 *

Warning: Small sample sizes. Use Caution.

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> .05 so variance is =

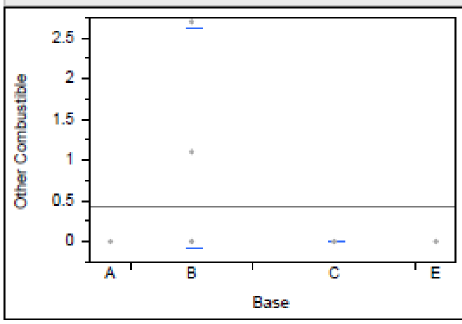
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.8425	1	2.0208	0.4547

Fit Y by X Group

Oneway Analysis of Other Combustible By Base



Excluded Rows 117

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	4.000	5.000	4.00000	-0.265
B	3	21.000	15.000	7.00000	1.945
C	4	16.000	20.000	4.00000	-1.174
E	1	4.000	5.000	4.00000	-0.265

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
4.5000	3	0.2123

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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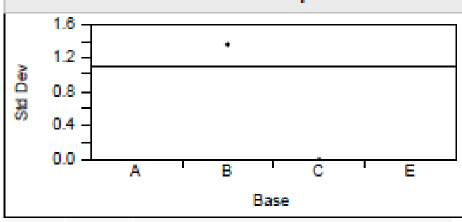
Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.0000000	0.000000
B	3	1.357694	0.9555556	1.266667
C	4	0.000000	0.0000000	0.000000
E	1	.	0.0000000	0.000000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.5397	1	5	719
Brown-Forsythe	82.5143	1	5	0.0003 *
Levene	8.2609	1	5	0.0348 *
Bartlett	.	1	.	<.0001 *

Warning: Small sample sizes. Use Caution.

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< .05 so variance is NOT =

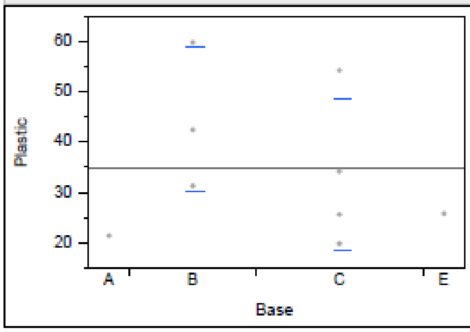
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
.	1	.	.

Fit Y by X Group

Oneway Analysis of Plastic By Base



Excluded Rows 117

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	2.000	5.000	2.00000	-0.968
B	3	21.000	15.000	7.00000	1.420
C	4	18.000	20.000	4.50000	-0.367
E	1	4.000	5.000	4.00000	-0.194

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
3.0667	3	0.3815

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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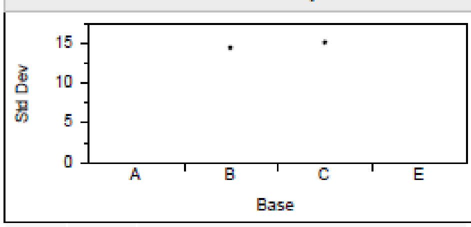
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.00000	0.00000
B	3	14.41157	10.22222	13.26667
C	4	15.09114	10.77500	10.77500
E	1	.	0.00000	0.00000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.0076	1	5	338
Brown-Forsythe	0.1800	1	5	0.6890
Levene	0.0082	1	5	0.9315
Bartlett	0.0042	1	.	0.9485

Warning: Small sample sizes. Use Caution.

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> .05 so variance is =

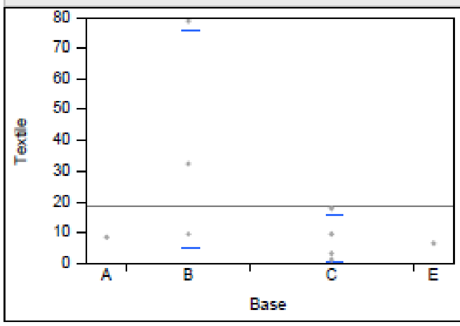
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.9751	1	4.5781	0.3727

Fit Y by X Group

Oneway Analysis of Textile By Base



Excluded Rows 117

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	4.000	5.000	4.00000	-0.194
B	3	22.500	15.000	7.50000	1.815
C	4	15.500	20.000	3.87500	-0.984
E	1	3.000	5.000	3.00000	-0.583

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
3.8739	3	0.2754

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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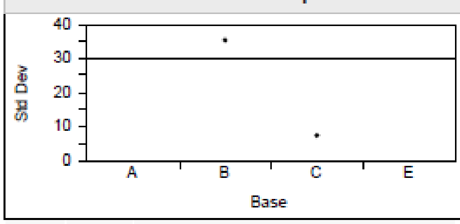
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.00000	0.00000
B	3	35.46059	25.82222	30.86667
C	4	7.51731	5.75000	5.75000
E	1	.	0.00000	0.00000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.3103	1	5	890
Brown-Forsythe	12.9105	1	5	0.0157 *
Levene	6.2581	1	5	0.0544
Bartlett	4.1714	1	.	0.0411 *

Warning: Small sample sizes. Use Caution.

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< .05 so variance is NOT =

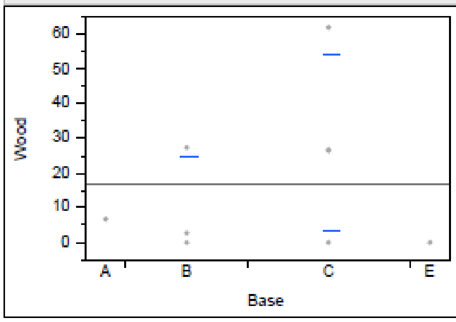
Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
2.4253	1	2.1355	0.2520

Fit Y by X Group

Oneway Analysis of Wood By Base



Excluded Rows 117

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A	1	5.000	5.000	5.00000	0.000
B	3	14.000	15.000	4.66667	-0.131
C	4	24.000	20.000	6.00000	0.872
E	1	2.000	5.000	2.00000	-0.985

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
1.8391	3	0.6065

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

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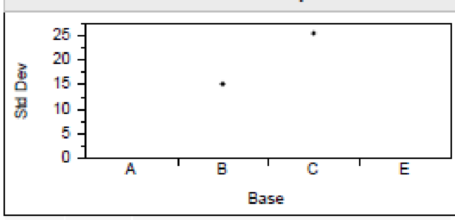
> .05 so medians are =

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
A	1	.	0.00000	0.00000
B	3	15.04294	11.53333	10.00000
C	4	25.39823	16.57500	15.55000
E	1	.	0.00000	0.00000

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.5322	1	5	[illegible]4984
Brown-Forsythe	0.2020	1	5	0.6719
Levene	0.2449	1	5	0.6417
Bartlett	0.4886	1	.	0.4846

Warning: Small sample sizes. Use Caution.

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> .05 so variance is =

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
1.4853	1	4.8659	0.2787

Appendix B

	Corrugated Cardboard	Food Waste	Liquid[a]	Misc Waste	Mixed Paper	Non-Comb	Other Comb	Plastic	Textile	Wood	Activity	Energy MMBtu	Energy kWh	kWh/37.5 #
IQR	23.9	17.7	22.85	34.25	29.9	9.15	0.55	24.9	20.35	27	Admin			
High	27.9	23.2	29.2	34.3	41.85	11.35	0.55	48.4	25.2	27	Admin	1.26	370.01	69.38
Low	4.00	5.50	6.35	0.05	11.95	2.20	0.00	23.50	4.85	0.00	Admin	0.33	97.07	18.20
IQR	43.25	76.88	8.68	0.00	31.33	9.55	0.00	14.63	0.03	0.58	DFAC			
High	49.45	145.40	8.68	0.00	32.38	10.23	0.00	28.28	0.03	0.58	DFAC	1.16	340.21	63.79
Low	6.20	68.53	0.00	0.00	1.05	0.68	0.00	13.65	0.00	0.00	DFAC	0.39	114.04	21.38
IQR	53.30	25.38	35.40	20.33	29.00	12.90	0.00	25.58	4.85	42.58	General			
High	70.55	31.63	35.78	20.33	32.83	14.60	0.00	46.35	4.85	42.58	General	1.46	427.41	80.14
Low	17.25	6.25	0.38	0.00	3.83	1.70	0.00	20.78	0.00	0.00	General	0.36	105.42	19.77
IQR	13.90	33.80	20.80	15.80	22.50	11.30	0.00	22.10	22.20	48.20	LSA			
High	18.50	35.70	28.10	15.80	37.30	13.60	0.00	40.60	22.90	48.20	LSA	1.14	335.10	62.83
Low	4.60	1.90	7.30	0.00	14.80	2.30	0.00	18.50	0.70	0.00	LSA	0.26	76.03	14.25
IQR	32.65	15.70	14.70	4.10	35.60	72.65	14.30	34.40	25.70	93.85	Motor Pool			
High	45.35	15.70	14.70	4.10	35.60	84.50	14.30	44.65	26.75	95.50	Motor Pool	1.69	494.87	92.79
Low	12.70	0.00	0.00	0.00	0.00	11.85	0.00	10.25	1.05	1.65	Motor Pool	0.21	61.04	11.44
IQR	32.90	1.30	0.00	0.00	25.70	7.90	15.40	39.60	3.50	140.20	SSA			
High	32.90	1.30	0.00	0.00	25.70	7.90	15.40	39.60	3.50	173.00	SSA	1.71	500.16	93.78
Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	32.80	SSA	0.15	44.27	8.30
IQR	38.95	76.13	19.58	4.43	37.10	16.30	0.00	56.25	10.05	59.98	Total			
High	33.10	75.50	19.58	4.43	35.75	15.08	0.00	42.20	10.05	59.98	Total	1.32	386.85	72.53
Low	5.85	0.63	0.00	0.00	1.35	1.23	0.00	14.05	0.00	0.00	Total	0.19	54.61	10.24

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Vita

Captain Daniel C. Amack entered undergraduate studies at Montana State University in Bozeman, Montana, where he graduated with a Bachelor of Science degree in Mechanical engineering in May 2009. He was commissioned through the Detachment 450 AFROTC at Montana State University where he was nominated for a Regular Commission.

In June 2009, he was assigned to the 27th Special Operations Civil Engineer Squadron, Cannon AFB, New Mexico, where he served as the Officer in Charge of Asset Management Flight. While stationed at Cannon, he deployed overseas in June 2011 to spend nine months in Jalalabad, Afghanistan, as the Deputy Engineer of Provincial Reconstruction Team Nangarhar. In September 2012, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the 5th Civil Engineer Squadron, Minot AFB, North Dakota.

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14. ABSTRACT Solid waste is generated in mass quantities at forward deployed locations due to their temporary nature. Current handling practices are inefficient and wasteful, and do not reuse the energy inherently available in the waste. This research identifies potential energy, convoy, and casualty reductions that can be realized through the use of waste-to-energy (WTE) at contingency locations. It identifies typical variance expected in the solid waste stream and illustrates decision factors for determining the type of WTE technology that is best suited for a particular situation. A statistical analysis was conducted on the waste streams of five contingency bases to determine energy content of a typical sample at any location for WTE planning purposes. Energy and risk reduction was calculated and a decision tree was developed to allow personnel to choose a technology type that would best suit their waste disposal needs. Results indicate that variability in the waste stream significantly affects results of each analysis and that the typical sample energy content from the entire waste stream is much lower than either of the other waste streams.						
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